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FEASIBILITY STUDY ON THE USE OF OPEN-WIRE TRANSMISSION LINES, CAPACITORS, AND CAVITIES TO MEASURE THE ELECTRICAL PROPERTIES OF VEGETATION

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ABSTRACT

Theory, design, and usefulness of experiments to measure effective complex dielectric constants in foliage and vegetation by means of rigid open-wire transmission lines are described. The frequency ranges 30 to 75 MHz (VHF) and 4 to 30 MHz (HF) are covered by using a 5/8-inch-diameter, 3-inch spacing line and a 4-inch-diameter, 40-inch spacing line, respectively. Use of these instruments allows one to place bounds on the macroscopic electrical parameters of foliage.

Results are presented of measurements with these equipments in October 1965 in the Hoh Rain Forest, Olympic National Park, Washington. There, in the most dense growth available, representative values of effective relative permittivity (ϵ_r) and effective conductivity (σ) were estimated to average about 1.2 and 8×10^{-5} mhos/meter, respectively. Similar measurements made in living California foliage in midsummer 1965 yielded $\epsilon_r \approx 1.1$ and $\sigma \approx 2 \times 10^{-4}$ mhos/meter. Such differences may be seasonal: The need for a catalog of electrical properties of vegetation is indicated.

An experiment relating the density of freshly cut willow boughs to the properties of the sample measured by the VHF transmission line is described in detail. From this, it is estimated that vegetation intrinsic conductivities are of the order 0.03 mhos/meter, or greater, in living willows during mid-October. The ϵ_r is linearly related to "biodensity" as indicated by the theory of the complex dielectric constant of mixtures.

Other methods of measurement, such as the use of large capacitors or resonant cavities, are discussed.

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ACKNOWLEDGMENT

The authors are pleased to acknowledge the excellent cooperation of Mr. Bennet T. Gale, Superintendent, and the Forest Rangers of the Olympic National Park, where much of the experimental work was performed.

I INTRODUCTION

This study was undertaken to develop and test new methods of measuring the effective complex dielectric properties of a living foliage medium, such as a forest or jungle, in the hope of establishing meaningful values of conductivity and permittivity, which might be used in modeling such a medium (theoretically) for estimating its effect on radio propagation. The problem of separating the effects of the forest medium from those of the underlying earth was first considered.

Some previous investigators have used transmission-line stubs to measure radio-propagation constants of earth. (See, for instance, Kirkscether.[1*]) Another technique for measuring the electrical constants of earth is curve fitting of measured values of path loss to calculated curves for various assumed ground constants.[2] When the curve-fitting method is used to determine the effective ground constants of forested terrain, it is difficult to separate the effects of the earth from those of vegetation. Thus, we decided to try using an open-wire transmission line in the foliage itself.[†] A rigid open-wire line (OWL) with easily variable length can be readily prepared, inserted into foliage of almost any density, and--by proper connection to an impedance-measuring device--be used to measure quantities related to the average dielectric constant and conductivity of the material within the envelope of sensitivity about the line.

The active sensing regions (quasi-TEM fields) of a two-wire open line of small (order of 10^{-2} λ) spacing are contained within, to a good

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* References are given at the end of the report.

† The idea for this application of open-wire transmission lines [see G. H. Hagn, "Transmission Line Measurements of Jungle Propagation Constant," Stanford Research Institute Project 4240 Memorandum (9 September, 1964)] came from a discussion with Dr. John Taylor, University of South Carolina, Columbia, South Carolina in the summer of 1964.

approximation, a sinusoid of revolution about the line axis; the regions of least sensitivity being in the vicinity of the voltage nodes in the standing-wave pattern on the line. The maximum radius of effect is found in the vicinity of the first voltage maximum of the line. The radius of effect varies with the standing-wave ratio on the line, the minimum possible being about 1/2 ft for the line of about 300 Ω characteristic impedance, which we constructed for use at VHF (see Fig. 1). The line had a spacing of several inches and an average radius of effect of about 2 ft. Thus, the OWL could be so positioned in a forest that it would be relatively insensitive to the ground below and the air above the forest when they were at a distance greater than the maximum radius of effect. Actually, the region of concentrated energy about the OWL is not large--Fig. 2* shows the percentage of electromagnetic power carried through a circle of given radius normal to the conductors of the OWL terminated in its characteristic impedance.

The frequency range of primary interest was 25 to 100 MHz. At 50 MHz, we found that ground effect could be eliminated entirely by placing the transmission line at a height greater than 3-4 ft. A line length of 0.75 λ or more was used to provide a long sensing region. Since sensitivity to the medium was negligible at a radius greater than 3-4 ft about the line, fringing effects can be ignored (see Fig. 1), and we can assume that the relative dielectric constant (ϵ_r) and conductivity (σ) obtained with the transmission line are the effective values for the air-foliage mixture near the transmission line.

If a portable generator is used to power the impedance meter, the entire apparatus can be moved about within a forest to obtain sufficient measurements to represent the average electrical character of the forest. The sensing envelope can be shifted axially both by lengthening the line (altering the standing-wave pattern) and by moving the entire apparatus, thus providing a statistical approach to the measurement.

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* Calculated by Dr. John Taylor, University of South Carolina, Columbia, South Carolina.

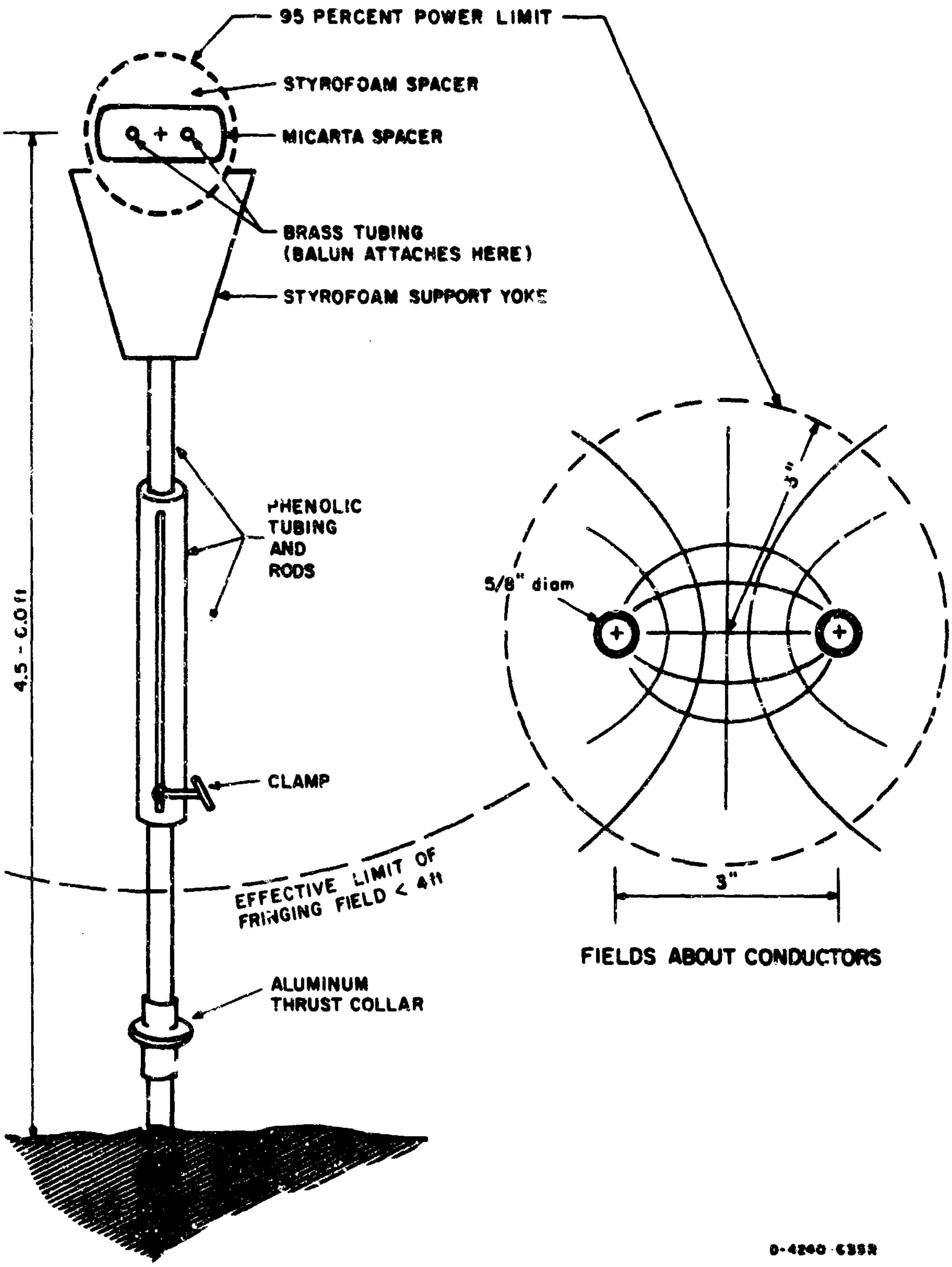

FIG. 1 SCHEMATIC AND END VIEW OF VHF OWL

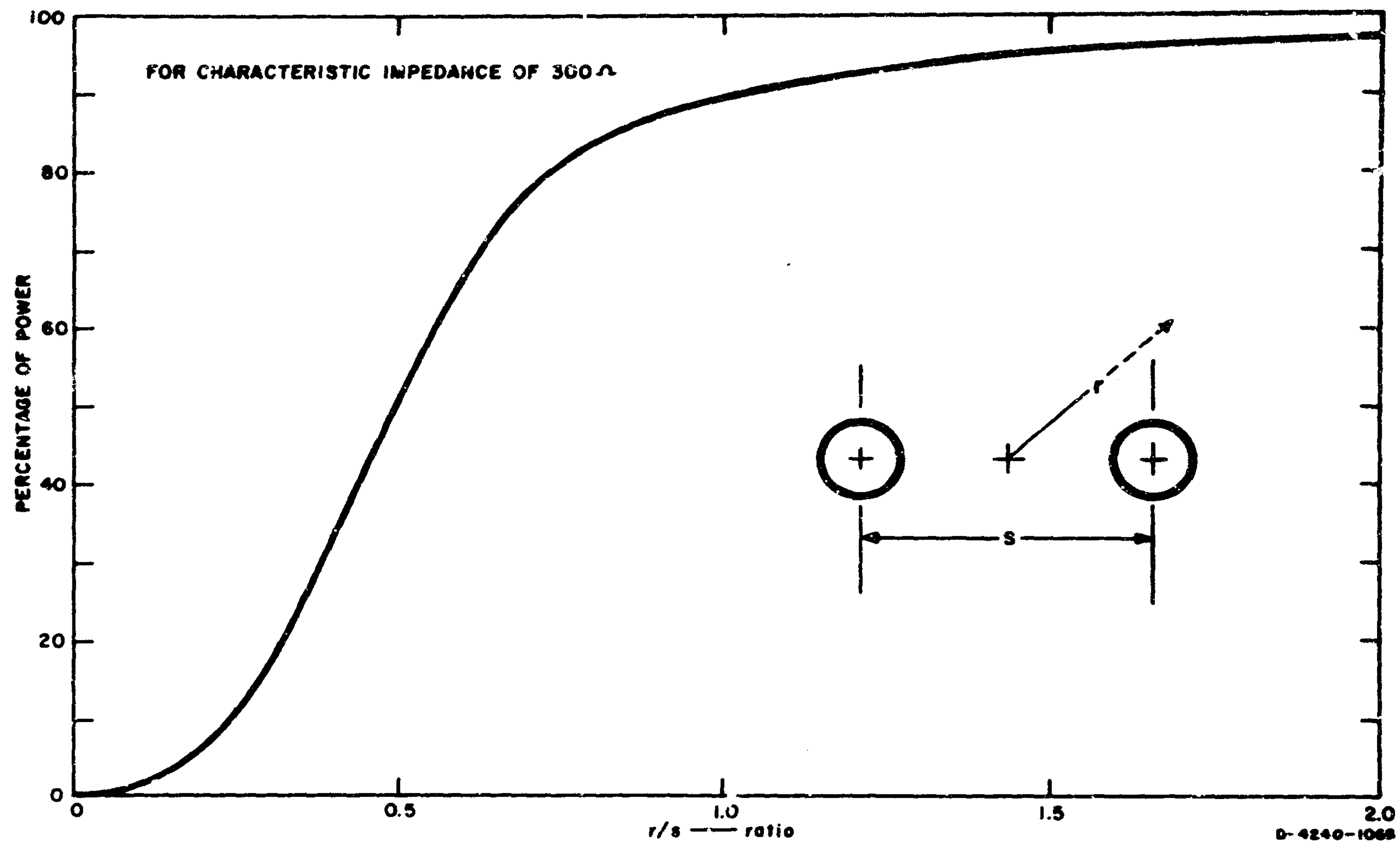

FIG. 2 RELATIVE POWE DISTRIBUTION IN THE VICINITY OF AN OWL

Alternatively, one can use a longer line and make fewer measurements for an equivalent sample size. The sample size is the number of active regions on the line per setup multiplied by the number of setups, although the number of independent samples is probably somewhat less than this number. For example, a 1-λ line could yield two samples per setup and the reading would give the average. Since the active region for a short-circuited line is just the reverse of that for an open-circuited line, care must be taken to select a sample that is fairly homogeneous in the axial direction of the line.

It was thought that the capability for rapid measurement would be improved if the line could be enclosed, for most of its length, within a dielectric cyclinder of low permittivity, to allow ease of movement in dense growth. We tested a 5-inch-diameter Fiberglas cylinder; preliminary indications were that when the line was immersed in vegetation it gave similar readings with and without the case. However, a more complete analysis of the results indicated that the value of ϵ_r obtained with the Fiberglas in place might be low by as much as a factor of 2.* The same factor would apply to other parameters, such as conductivity σ or loss tangent δ.

We do not envision operation with line lengths greater than 25 ft (about 1.25 to 1.5 λ at 50 MHz), so that the apparatus can be hoisted into the tree canopy to obtain vertical-profile information.

Another possible method of measuring propagation constants in foliage that was not tried is to construct a large screen-wire cavity in the growth and measure its resonant frequency and Q. The measurement could be repeated (in its essentials) in air, to provide an effective set of parameters for the foliage alone. Likewise, a large capacitor (one-sixth of a cavity) could be used. In addition to the construction problem, the cavity Q measurement almost precludes a statistical approach--and the selection of a "typical" volume of foliage presents

* The experiment in the appendix indicated that a factor of less than 1.6 was involved.

considerable difficulties. The value of such a measurement would probably lie in its use as an independent method of "calibrating" the transmission line and for testing the effects of changes in air moisture and temperature. Consequences of seasonal or artificial defoliation at a fixed site might also be studied by such an experiment.

Besides measurements in foliage, tests in air must be made for comparison. These should be almost identical to the foliage tests, with respect to line length, frequency, positions of dielectric separators on the line, and (probably) air humidity and temperature. Such control data might be taken in small clearings of a forest.

II THEORETICAL ASPECTS

A. GUIDED WAVES

The propagation of guided electromagnetic waves on open-wire transmission lines depends in part upon the properties of the medium in which the wires are immersed. The equations* describing waves propagating along a transmission line can be written:[3]

$$\frac{\partial i}{\partial x} = gv + C\frac{\partial v}{\partial x} \quad ; \quad \frac{\partial v}{\partial x} = ri + L\frac{\partial i}{\partial t} \quad ,$$

where

i = current

v = voltage

g = susceptance per unit length

x = distance down the line

C = capacitance per unit length

r = resistance per unit length

L = inductance per unit length.

The two preceding equations can be combined to give the wave equation.

For the sinusoidal steady-state solution of the wave equation, it is convenient to define a propagation "constant," Γ:

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* In this development we assume that TEM waves propagate on the transmission line. Actually, the presence of the lossy dielectric permits a small longitudinal E component to exist, so that the waves are TM. We consider the quasi-TEM approach an excellent approximation for foliage dielectrics, since the longitudinal components should average to zero in this case. A similar approach was used with success in measuring dielectric properties of earth.[1]

$$\Gamma = \sqrt{zy} = \alpha + j\beta \quad ,$$

such that

$$\nabla^2 V = \Gamma^2 V \quad ,$$

where

$V = v \sin \omega t$

α = attenuation constant

β = phase constant

$z = r + j\omega L$ = impedance per unit length

$y = g + j\omega C$ = admittance per unit length

$\omega = 2\pi f$ = radian wave frequency

f = frequency

$j = \sqrt{-1}$

The quantity $\sqrt{z/y}$ (where z and y are defined as above) is a significant parameter and is termed the characteristic impedance, Z_o. This quantity is most meaningful for a medium that is at least locally homogeneous. The model of the foliage assumed for the following discussion is that of a lossy dielectric slab that is locally homogeneous on a macroscopic scale. That is, the medium can be described* by an effective σ and ϵ that are functions of frequency and the environment. Clearly, such a model will not apply for all forests, frequencies, etc.

By holding x constant, the characteristic impedance, Z_o, may be obtained from two measurements of the open-wire line impedance: one with shorted termination, Z_{sc}, and one with open termination, Z_{oc}. Then,

$$Z_{sc} = Z_o \tanh \Gamma x$$

$$Z_{oc} = Z_o \coth \Gamma x$$

---

* The permeability of the medium is assumed to be essentially that of a vacuum; that is, $\mu = \mu_o = 4\pi \times 10^{-7}$ Henry/meter

and

$$Z_o = (Z_{oc} Z_{sc})^{1/2} \quad .$$

In practice, we found that x for such measurements should be ±0.06 to ±0.19 λ_m different from the resonant line length* to balance open- and short-circuit effects (λ_m denotes the wavelength in the medium).

It is convenient to define a loss tangent by considering that the medium through which the wave travels can be described by a complex dielectric constant $\epsilon' = \epsilon - j\epsilon''$, where ϵ is the usual dielectric constant, and the loss tangent, δ, is thus ϵ''/ϵ (that is, the tangent of the angle between real and imaginary parts of the complex dielectric constant). The meaning of this loss tangent and the relationships between α and β and σ and ϵ are best seen from the following development. From one of Maxwell's equations,[4] the curl of magnetic field intensity is:

$$\nabla \times \bar{H} = \bar{i} + \frac{\partial \bar{D}}{\partial t}$$

$$\bar{D} = \epsilon$$

$$\bar{i} = \sigma \bar{E} \quad ,$$

where

$\bar{H}$ = magnetic field intensity vector

$\bar{D}$ = electric flux density vector

$\bar{E}$ = electric field intensity vector

$\bar{i}$ = current density vector.

It can be seen here that σ and ϵ, both real numbers, are properties of the dielectric medium. For the case of a forest medium that is locally homogeneous on a macroscopic scale, they should be thought of as mean effective values.

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* More generally, the condition is $\beta x = (2n + 1)(\pi/4)$, $n = 0, 1, 2....$ or $x = (2n + 1)(\lambda_m/8)$.

For

$$\bar{E} = \bar{E}_o e^{j\omega\left(t - \frac{qx}{c}\right)} ,$$

where c is velocity of light and q is refractive index, and assuming time invariance ($e^{j\omega t}$ constant), we get

$$\frac{\partial \bar{D}}{\partial t} = \epsilon \frac{\partial \bar{E}}{\partial t} = \epsilon \bar{E}(j\omega) ,$$

and the curl is

$$\nabla \times \bar{H} = (\sigma + j\omega\epsilon)\bar{E} .$$

One can define a complex dielectric constant ϵ' such that

$$j\omega\epsilon' = \sigma + j\omega\epsilon$$

$$\epsilon' = \epsilon - j\frac{\sigma}{\omega} .$$

Defining a complex relative dielectric constant

$$\epsilon_r' = \frac{\epsilon'}{\epsilon_o} \text{ analogous to } \epsilon_r = \frac{\epsilon}{\epsilon_o} \text{ for real variables} ,$$

where

$$\epsilon_o = 8.84 \times 10^{-12} \text{ Farad/meter (rationalized MKS units)} ,$$

we get

$$\epsilon_r' = \epsilon_r - j\frac{\sigma}{\omega\epsilon_o} .$$

In these terms, the loss tangent, δ, is $\sigma/\omega\epsilon_r\epsilon_o = \sigma/\omega\epsilon$. Obviously, a small loss tangent implies a good dielectric and vice versa. Now, we desire to relate this to α and β, the real and imaginary parts of the propagation constant.

For a wave propagating as $\exp(-\Gamma x)$ in the +x direction, we get, from the foregoing,

$$j \frac{\omega q}{c} = \Gamma = \alpha + j\beta \quad .$$

But $q = (\epsilon_r')^{1/2}$

Thus,

$$j \frac{\omega}{c} \left(\epsilon_r - j \frac{\sigma}{\omega\epsilon_o}\right)^{1/2} = \alpha + j\beta$$

or

$$-\left(\frac{\omega}{c}\right)^2 \left(\epsilon_r - j \frac{\sigma}{\omega\epsilon_o}\right) = \alpha^2 - \beta^2 + 2j\alpha\beta \quad .$$

By equating real and imaginary parts,

$$\left(\frac{\omega}{c}\right)^2 \epsilon_r = \beta^2 - \alpha^2 \quad ; \quad \alpha = \left[\beta^2 - \left(\frac{\omega}{c}\right)^2 \epsilon_r\right]^{1/2}$$

$$\frac{\omega\sigma}{c^2\epsilon_o} = 2\alpha\beta \quad ; \quad \beta = \frac{1}{2\alpha} \frac{\sigma\omega}{c^2\epsilon_o} \quad .$$

Or, for known α and β:

$$\epsilon_r = \left(\frac{c}{\omega}\right)^2 (\beta^2 - \alpha^2)$$

$$\sigma = 2\alpha\beta \frac{c^2\epsilon_o}{\omega} \quad .$$

Thus, by use of the above equations, determining α and β is equivalent to determining σ and ϵ. The expressions separate so that

$$\alpha^2 = \frac{1}{2}\left(\frac{\omega}{c}\right)^2 \left\{\left[\epsilon_r^2 + \left(\frac{\sigma}{\omega\epsilon_o}\right)^2\right]^{1/2} - \epsilon_r\right\}$$

$$\beta^2 = \frac{1}{2}\left(\frac{\omega}{c}\right)^2 \left\{\left[\epsilon_r^2 + \left(\frac{\sigma}{\omega\epsilon_o}\right)^2\right]^{1/2} + \epsilon_r\right\} .$$

To determine Γ, however, a check is quite advisable. The following approximate approach can be used with confidence provided the medium containing the OWL is not extremely lossy (that is, ARG $Z_o < 10^o$). For the TEM mode,

$$\lambda_{\substack{\text{medium}\\ \text{TEM}}} = \frac{2\pi}{\beta} .$$

One can thus tune the line (using a "trombone") to short circuit resonance and measure the length of N (odd) quarter-wavelengths to find λ_m and hence β. The ambiguity represented by N above may be resolved by placing a hand in the vicinity of the line as described in Sec. VI. Similarly, open-circuit resonance at N half-wavelengths may be used. The value of β thus found can be used to check the value determined from the impedance measurements.

The attenuation constant, α, can also be found simply from the short-circuit-resonance data, when Z_o is computed from other impedance measurements, since at resonance:

$$\frac{Z}{Z_o} = \tanh(\Gamma x) = j\,\frac{\sin\beta x \cosh\alpha x - j\cos\beta x \sinh\alpha x}{\cos\beta x \cosh\alpha x + j\sin\beta x \sinh\alpha x} .$$

$$\sin\beta x = \pm 1 ,$$

$$\cos\beta x = 0 ,$$

and

$$\frac{Z}{Z_o} = \frac{j\cosh\alpha x}{j\sinh\alpha x} = \coth\alpha x \quad , \quad \text{or } \tanh\alpha x = \frac{Z_o}{Z} .$$

The low-loss approximation may be used if Z_o/Z is less than 0.15, since

$$\tanh \alpha x \approx \alpha x \quad ;$$

then

$$\alpha \approx \frac{Z_o}{xZ} \quad .$$

The foregoing equations also apply to open-circuit resonance at N half-wavelengths.

The corresponding relations for open-circuit resonance at N (odd) quarter-wavelengths are:

$$\frac{Z}{Z_o} = \tanh \alpha x$$

$$\alpha \approx \frac{Z}{xZ_o} \quad , \quad \text{if } \frac{Z}{Z_o} \text{ is less than 0.15} \quad .$$

B. CAVITY RESONATORS

At high frequency, radiation can be reduced by the use of resonant cavities in place of conductors, and the development of wave behavior in cavities is similar to that discussed for transmission lines. It has been shown that, for a rectangular cavity, the requirements for resonance are:[4]

$$\lambda_m = \frac{2\ell w}{(\ell^2 + w^2)^{1/2}} \quad , \quad \text{or } f_r = \frac{1}{2\ell w}\left(\frac{\ell^2 + w^2}{\mu\epsilon}\right)^{1/2} \quad ,$$

where

f_r = resonant frequency

λ_m = wavelength in the medium filling the cavity (TE_{10} mode)

ℓ = length of cavity in the direction of wave propagation

w = width of cavity across the direction of propagation.

The remaining dimension of the cavity, height, need not be specified for the TE_{10} mode, since its electric field must terminate at the cavity top and cavity bottom, regardless of their separation (within reason). The TE_{10} wave is cut off at

$$\lambda_c = 2w$$

$$f_c = \frac{1}{2w\sqrt{\mu\epsilon}} = \frac{\nu_p}{2w} = \frac{c}{2w\sqrt{\epsilon_r}} ,$$

where ν_p is phase velocity.

Therefore the cavity cutoff frequency is independent of height. Other considerations place bounds on height, however. Small height will increase the possibility of voltage breakdown across the cavity. It will also increase attenuation in the cavity waves because of conductor losses. On the other hand, large height permits propagation of higher-order modes, with consequent energy losses. The waveguide height/width ratio most consistent with good engineering practice is about 1:2.

To obtain the propagation constants, if the resonant frequency of the cavity is known,

$$f_r = \frac{1}{2\ell w}\left(\frac{\ell^2 + w^2}{\mu\epsilon}\right)^{1/2} ,$$

as we had from the cavity dimensions. Then, if $\mu = \mu_o$, and two measurements are made, one with air and one with foliage in the cavity, ϵ_r may be obtained as

$$\epsilon_r = \left(\frac{f_o}{f_r}\right)^2 ,$$

where

f_o = resonant frequency for air

f_r = resonant frequency for foliage.

The quality ratio, Q, of a resonant cavity is given approximately (at high Q values, nearly exactly) by:

$$\frac{1}{Q} \approx \frac{\Delta f}{f_r} \quad ,$$

where Δf represents the -3-dB amplitude bandwidth of the cavity.

The Q due to an imperfect dielectric filling the resonator is given by

$$\frac{1}{Q} = \frac{\sigma}{\omega \epsilon_r \epsilon_o} = \delta \quad ,$$

the loss tangent for the dielectric (discussed earlier in connection with the definition of complex dielectric constant). Thus,

$$\delta = \frac{\sigma}{\omega \epsilon_r \epsilon_o} \approx \frac{\Delta f}{f_r} \quad ,$$

and

$$\sigma \approx \frac{\Delta f}{f_r} \omega \epsilon_o \left(\frac{f_o}{f_r}\right)^2$$

$$\approx \omega \epsilon_o \Delta f \frac{f_o^2}{f_r^3} \quad .$$

The above development provides the mean effective values of ϵ_r, σ, and δ for a homogeneous lossy dielectric enclosed by a resonant cavity whose resonant frequency and Q are known.

Cavity Q (air dielectric) can be computed readily as a check to see whether a cavity has high enough Q to be useful for the type of measurement described above. For a square cavity ($\ell = w$):

$$Q = \frac{\pi \eta}{2 R_s} \frac{h\sqrt{2}}{2h + w}$$

R_s = surface resistivity

$\eta = \sqrt{\mu_o/\epsilon_o} = 377\Omega$ = intrinsic impedance of free space

h = cavity height

w = cavity width, length.

The calculation could be repeated for other dielectrics than air by replacing ϵ_o with the appropriate ϵ (which will usually be complex for living vegetation).

C. PARALLEL-PLATE CAPACITORS

The dielectric characteristics of parallel-plate capacitors may be represented mathematically by

$$C = \epsilon_o \epsilon_r \frac{A}{S} \quad ,$$

where

A = area of one plate

S = plate separation

ϵ_r = relative dielectric constant of the material between the plates.

Since

$$C = \frac{-j}{\omega X_c} \quad ,$$

and (assuming A and S constant) with $\epsilon_r = 1$ for air, we may find, for the foliage:

$$\epsilon_r = \frac{C_{foliage}}{C_{air}} = \frac{X_{c\ air}}{X_{c\ foliage}} \quad ,$$

when two measurements of impedance are made with the capacitor, one using air and the other using a foliage dielectric. Conductivity values are found as follows:

$$Q = \frac{X_c}{R} = \omega C_p R_p$$

$$= \frac{\omega \epsilon_o \epsilon_r}{\sigma}$$

$$\sigma = \frac{\epsilon_o \epsilon_r}{C_p R_p}$$ if a paralleled impedance bridge is used ,

or

$$\sigma = \omega \epsilon_o \frac{R}{X_c} \epsilon_r$$ if a series impedance bridge such as the General Radio 1616-A is used ,

where R_p and C_p are the shunt values for an RC parallel combination (such as one would measure with the Boonton 250A RX meter) of impedance components measured with foliage as a dielectric. To be precise, one should account for the fact that the capacitor does not have infinite Q when filled with the air dielectric. However, when the Q of the capacitor loaded with foliage is much less than in air (by a factor of 10 or more), the error thus introduced is negligible for our purposes.

In practice, it may be necessary to form the condenser with a taper in each plate to provide a symmetrical feed at high frequencies. In such a case, all the plate area may not be equally active in the measurements, and the following equation should be used for ϵ_r:

$$\epsilon_r = \frac{C_f}{C_a} \frac{A_a}{A_f} = \frac{A_a}{A_f} \frac{X_a}{X_f} ,$$

where

f = a foliage-dielectric measurement

and a = an air dielectric measurement,

the value of ϵ_r thus obtained being used to find σ.

The area A_r can be calculated from the dimensions of the portion of the parallel-plate capacitor that encloses the foliage. But A_a must be measured, since it includes the tapered portion of the capacitor input as well. Then A_a becomes the effective area of one side of a parallel-plate capacitor of the same thickness, S, used in measuring the foliage, and which has the same capacitance as that found for air (C_a),

$$A_a = \frac{S}{-X_a \omega \epsilon_o} \quad .$$

It may be possible, however, to trim the foliage so that the ratio of C's gives ϵ_r directly as for the case of truly parallel plates.

D. PROPERTIES OF THE MODEL DIELECTRIC-SLAB MEDIUM

If the foliage is considered to present a uniform dielectric medium* of permeability $\mu = \mu_o (4\pi \times 10^{-7}$ H/m), then only the mean effective values of the dielectric constant, ϵ, and the conductivity, σ, remain to be specified. This may be done by noting that the dielectric-slab medium is a model for a mixture of two media--air and foliage--and by determining the constants for the equivalent medium.

Dielectric properties of mixtures are discussed in the Encyclopedia of Physics[6] as follows:†

Let the elements of a mixture have dielectric constants

$$\epsilon_1, \epsilon_2, \ldots \epsilon_n$$

with the corresponding elements occupying fractions of the total volume

$$F_1, F_2, \ldots F_n \quad .$$

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* A more comprehensive model for a forest medium, having some properties of dielectric lenses, has been proposed by Pounds & Le Grone.[5]

† This discussion was first brought to the attention of the authors by Dr. Bernard Lippmann of Defense Research Corporation, Santa Barbara, California.

Then the mean dielectric constant, ϵ_m, is bounded by $\overline{\epsilon_m} > \epsilon_m > \underline{\epsilon_m}$, where

$$\overline{\epsilon_m} = \sum_{i=1}^{n} \epsilon_i F_i \quad \text{(dielectric slabs in parallel)}$$

and

$$\underline{\epsilon_m} = \left(\sum_{i=1}^{n} \frac{F_i}{\epsilon_i} \right)^{-1} \quad \text{(dielectric slabs in series)} \quad .$$

With the replacement of ϵ by σ in the above relation, the equations apply to conductivity. In the case of a mixture containing air, however, the lower limit of the mean conductivity is zero, so

$$\overline{\sigma_m} > \sigma_m > 0$$

where

$$\overline{\sigma_m} = \sum_{i=1}^{n} \sigma_i F_i \quad .$$

If shapes and orientations of constituents can be specified, the two limits discussed above may be abandoned in favor of a discrete solution of the mixture problem.*

If the vegetation has a relative dielectric constant of 80, corresponding to that of water, and occupies a fraction F of the total volume ($F \ll 1$), the limits on ϵ_m become

$$(1 + 79F) > \frac{\epsilon_m}{\epsilon_o} > 1 \quad .$$

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* Developments of this approach may be found in Refs. 7 and 8.

If σ_v is the conductivity of the foliage, the limits on σ_m are

$$\sigma_v F > \sigma_m > 0 \quad .$$

Remembering that the complex relative dielectric constant was given as

$$\epsilon_r' = \epsilon_r - j\frac{\sigma}{\omega\epsilon_o} \quad ,$$

We can estimate that, for the mixture,

$$\epsilon_r' \approx (1 + 79F) - j\frac{\sigma_v F}{\omega\epsilon_o} \quad ,$$

the upper limits on σ_m and ϵ_m being taken as approximate values. To gain α and β for the mixture, recall that

$$\beta^2 = \frac{1}{2}\left(\frac{\omega}{c}\right)^2 \left\{\left[\epsilon_r^2 + \left(\frac{\sigma}{\omega\epsilon_o}\right)^2\right]^{1/2} + \epsilon_r\right\}$$

$$\alpha = \frac{1}{2\beta}\left(\frac{\omega}{c}\right)^2 \frac{\sigma}{\omega\epsilon_o} = \frac{\omega\,\mu_o\sigma}{2\beta} \quad .$$

Now let $\sigma_v F = \bar{\sigma}$, and note that $\epsilon_r = (1 + 79F) \approx 1$ when $F \ll 1$. Thus the expression for β^2 becomes simplified at high frequencies when losses are not too great (that is, when $\omega\epsilon_o \gg \bar{\sigma}$). For this case,

$$\epsilon_r^2 \gg \left(\frac{\bar{\sigma}}{\omega\epsilon_o}\right)^2 \quad .$$

and we may estimate that

$$\beta \approx \frac{2\pi}{\lambda_o}(1 + 79F)^{1/2}$$

$$\alpha \approx \frac{\bar{\sigma}}{2}\left(\frac{\mu_o}{\epsilon_o}\right)^{1/2} (1 + 79F)^{-(1/2)} \approx 60\pi\bar{\sigma}\,(1 + 79F)^{-(1/2)}$$

Assuming $79F \ll 1$, and using the first-order terms of the binomial expansion, we further approximate:

$$\beta \approx \frac{2\pi}{\lambda_o}(1 + 39.5F)$$

$$\alpha \approx 60\pi\,\bar{\sigma}\,(1 - 39.5F) \quad .$$

E. SCATTERING

The bounds given on σ and ϵ in Sec. II-D are strictly correct only in the case of low frequencies ($kr \to 0$, where $kr = 2\pi r/\lambda_o$ and r is the longest linear dimension of the vegetation). A more accurate determination requires a solution of the scattering problem that the actual vegetation presents.*

We note, without formal proof, after a development by Lippmann,† that if $f(s)$ is the forward-scattered amplitude, the complex propagation constant defined in Sec. II-A is given by

$$\Gamma = \alpha + j\beta = d\lambda_o^2 f(s) \quad ,$$

where d is the density of scattering elements.

If the volume per scatter element is V, and the fractional volume (with air in mixture) is $F = dV$, we have the same problem as that treated under dielectric mixtures and can develop

$$\alpha = \frac{F\lambda_o^2}{V}\,[\text{Imaginary part of } f(s)] \quad , \quad \text{nepers/meter}$$

F = fractional volume, as before.

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* A realistic model of a forest as a dielectric could not be readily handled mathematically. Empirical investigation *in situ* is necessary.

† Dr. Bernard Lippmann, "The Jungle as a Communication Network," working paper, Defense Research Corporation, Santa Barbara (September 30, 1964), Private Communication.

For a scatterer having dimensions much smaller than the operational wavelength, we can calculate $f(s)$ readily by using the spherical Born approximation to give a rough correction. The result is

$$\text{Imaginary part of } f(s) = \frac{\pi^2}{\lambda_o^3} \frac{\sigma_v}{\omega\epsilon_o} V \quad ,$$

which combines with the first expression to give

$$\alpha \approx \frac{F\sigma_v}{2}\left(\frac{\mu_o}{\epsilon_o}\right)^{1/2}$$

$$\approx 60\pi\bar{\sigma} \quad .$$

This is the same as the expression for α developed in Sec. II-D, if $\epsilon_r \approx 1$ [that is, if $(1 - 39.5F) \approx 1$].

The above development assumes that the field within the scatterer is the same as that outside it. A first-order correction to this assumption is to adjust the amplitude of the internal field by a factor, $2/(1 + \sqrt{\epsilon_r})$, corresponding to the transmission coefficient which governs the transmission from vacuum into a dielectric slab of relative dielectric constant ϵ_r. If the scatterers are spheres of radius r, we find that the above result for α must be multiplied by the factors

$$\frac{2}{1 + \sqrt{\epsilon_r}} \frac{3}{(kr\sqrt{\epsilon_r})^2}\left[\frac{\sin kr\sqrt{\epsilon_r}}{kr\sqrt{\epsilon_r}} - \cos kr\sqrt{\epsilon_r}\right] \quad , \quad k = \frac{2\pi}{\lambda_o} \quad .$$

In the limit as $kr \rightarrow 0$ (low-frequency approximation), only the first factor is used, the remainder approaching unity.

F. QUANTITATIVE ESTIMATES OF THE PROPERTIES OF THE DIELECTRIC-SLAB MODEL

We are now in a position to assign reasonable values to the parameters developed above, in order to estimate the magnitudes of α and β in the model:

(1) For the fractional volume of vegetation, let

$$F = 10^{-3} \quad .$$

(2) For the permittivity of foliage, we use that of water,

$$\epsilon_r = 80 \quad .$$

(3) For the conductivity of foliage, we estimate from tables giving fresh lake water conductivities (the foliage may actually have greater conductivity*):

$$\sigma_v = 10^{-2} \text{ mho/meter} \quad .$$

(4) For the radius of spherical scattering elements, using the upper limit of the approximations and assuming $r \ll \lambda$:

$$r = 0.1 \text{ meter} \quad .^{\dagger}$$

(5) The operating frequency is taken as 50 MHz ($\lambda_o = 6$ meters).

Then

$$\bar{\sigma} = F\sigma_v = 10^{-5} \text{ mho/meter} \quad .$$

The scattering correction factor is 0.964,† and the estimated value for attenuation is found as

$$\alpha \approx 60\pi \, \bar{\sigma} \, (0.964)$$

$$\approx 1.82 \times 10^{-3} \text{ neper/meter} \quad .$$

---

* We subsequently found $\sigma_v > 10^{-2}$ mho/meter in the experiment described in the Appendix.

† The radius of such a scatterer required to cause a 10-percent correction (that is, a scattering factor of 0.9) is about 0.101 meter at 50 MHz (0.0172λ).

For comparison, we compute α by the approximation of Sec. II-D, which neglects scattering:

$$\alpha \approx 60\pi \bar{\bar{\sigma}} (1 + 79F)^{-(1/2)}$$

$$\approx 1.81 \times 10^{-3} \text{ neper/meter} \quad .$$

For an approximate value of β, we have, from Sec. II-B,

$$\beta \approx \frac{2\pi}{\lambda_o} (1 + 79F)^{1/2}$$

$$\approx 1.09 \text{ radian/meter} \quad .$$

This last value corresponds to an effective relative dielectric constant of 1.08 for the foliage/air mixture.

III EXPERIMENTAL EQUIPMENT

A. VHF OWL AND ACCESSORIES

The basic instrument required for the two-wire open-transmission-line measurements is an impedance bridge with a wide dynamic range and accuracy better than 1 percent. We have used a Boonton RX-meter (Model 250-A), having a frequency range of 5 to 250 MHz and capable of accurate measurements from about 20 Ω to 10 kΩ. With the use of a 4:1 coax balun impedance transformer to match the balanced transmission line to the unbalanced RX-meter input, the Boonton instrument's range has been quite satisfactory above about 40 MHz. A General Radio impedance bridge (Model 1606-A) has been used at the lower frequencies.

Several half-wavelength (resonant) coax balun transformers were made for trial (25-, 50-, 75-, and 100 MHz) purposes, but only the 50- and 75-MHz baluns have been used extensively in measurements to date. At resonance, the baluns have a transfer ratio of very nearly MOD 4.0, ARG 0°. All baluns were cut from RG-8/AU cable and fastened to the bridge through N-type connectors. Several toroidal baluns have been wound to give transfer ratios of 1:1. These can be used with both bridges.

The coax baluns are attached by thumbscrews to an input adapter made of two threaded 3-inch sections of 5/8-inch tubing. This short adapter section is treated electrically as part of the balun (and was included as such when the baluns were trimmed to their resonant lengths). A spare adapter section, identical with that just described, is used in tuning the impedance bridge to the resonant frequency of the balun before connection is made to the transmission-line assembly.

The balanced transmission line was made of 5/8-inch brass tubing cut in 1-meter sections with threaded joints. Termination is effected by using a trombone section with 9/16-inch brass tubing sliding in the last section of 5/8-inch tubing, variable in length by about 3/4 meter.

The change in conductor radius at the sliding joint is 0.028 inch. The end of the trombone section can be left open or be shorted by a 15-inch aluminum disc attached by thumbscrews. (See Figs. 3 through 7 for details.)

The two conductors of the transmission-line assembly are held at a 3-inch spacing by styrofoam discs (2-by-5-inch diameter) bored to accept the tubing. This spacing was selected as a compromise between a lossier (radiation) wide spacing and the undesirable proximity effects arising from close spacing. The input adapter and terminal trombone tubes were force-fitted into Micarta ($\epsilon_r = 4.6$) spacers of 3/8-inch thickness for rigidity. The styrofoam spacers ($\epsilon_r = 1.03$) slip over the tubing and fit snugly inside a cylindrical Fiberglas casing (1/16-inch thick and 5 inches in diameter) which protects the tubing, improves ease of handling, and can be removed after insertion of the OWL into the sample.

For the 3-inch spacing, the characteristic impedance may be calculated from geometrical considerations, as follows:

$$Z_o \approx 276 \log_{10}\left(\frac{S}{a}\right) = 271\Omega \quad ,$$

where a is the conductor radius and S is the conductor spacing. The measured values were somewhat higher than this, probably because of the finite conductivity of brass and the effect of the spacers and insulation coating. They fell in the range of 295 to 330Ω.

The spacers are placed at about 1-meter intervals along the transmission line, and each is supported by telescoping phenolic tubing, which can be forced into the ground. The terminal spacer is left unsupported. The supports may be adjusted in height from 4.5 to 6 ft.

Ten standard 1-meter tubular-conductor sections and two 0.5-meter conductor sections were fabricated to allow 50-MHz measurements to be made with a 1.5-λ (6-meter) line, if desirable. Except for the inner

FIG. 3 R-X METER AND COAX BALUN WITH EARLY VERSION OF VHF OWL

FIG. 4 ASSEMBLY OF VHF OWL WITH FIBERGLAS CASE

FIG. 5 INSERTION OF VHF TROMBONE TERMINATION

FIG. 6 VHF OWL WITHIN FIBERGLAS CASE

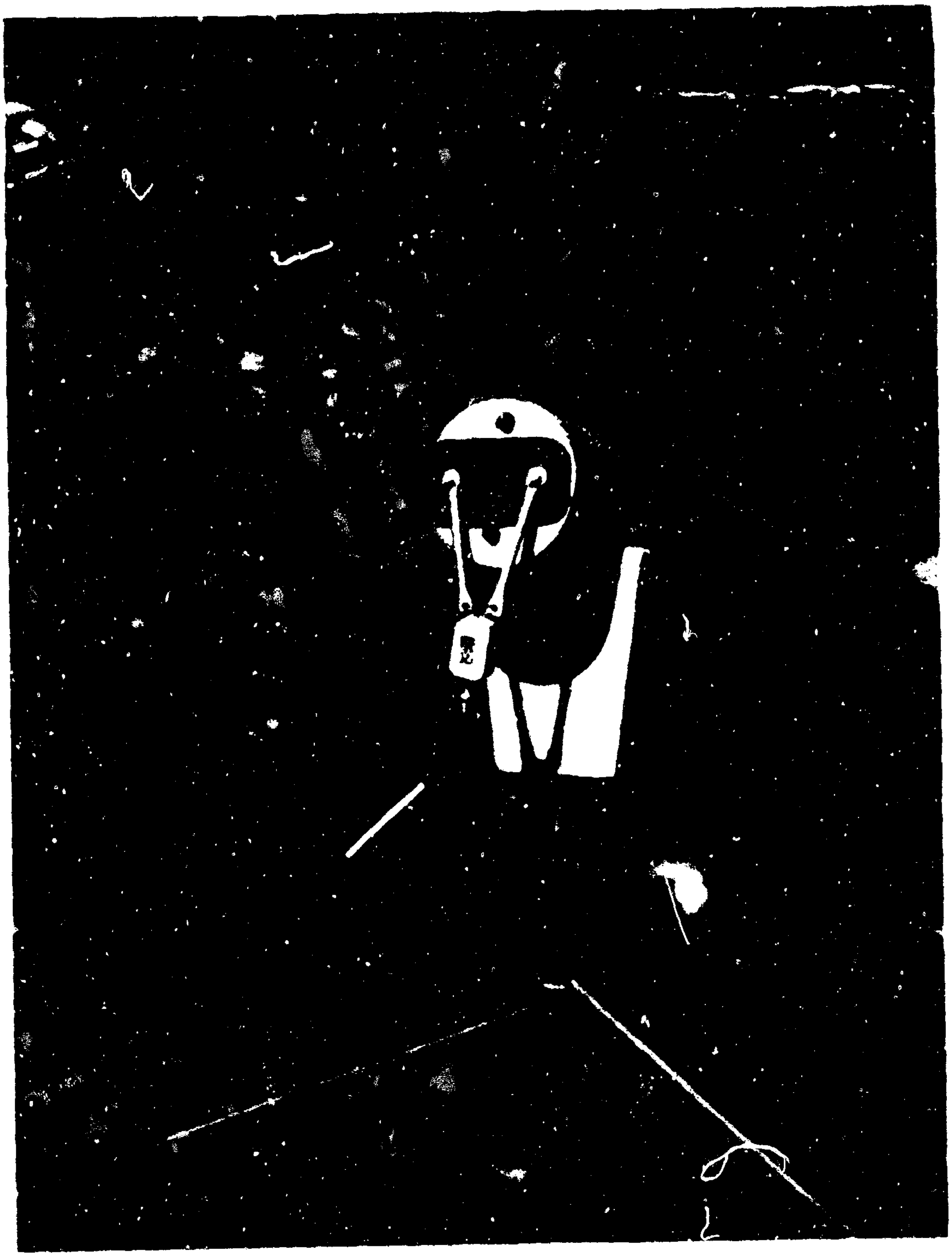

FIG. 7 TOROID BALUN INPUT TO VHF OWL

trombone sections, all conductor tubing was sprayed with Krylon* to resist corrosion (the line has since been silver-plated).

In Several instances (Sec. IV-C, Appendix) we have used the transmission line enclosed in the thin-walled Fiberglas cylinder to allow insertion into extremely dense vegetation. The cylinder has often been supported by vegetation. We have actually used two Fiberglas cylinders, one 4 meters long, with an additional cylinder 2 meters long that can be sleeve-fitted as an extension to cover the trombone termination. This case allows for rapid experimental setup, but we advocate its removal if accurate estimation of foliage effects is desired.

B. HF OWL

Several lengths of standard 4-inch aluminum irrigation pipe have been fitted with sleeve connectors and are being used as a transmission line probe at frequencies below 30 MHz. Connecting surfaces were silver-plated to prevent galling and corrosion. The apparatus is shown in Figs. 8 and 9.

Twelve 20-ft sections of the pipe provide a two-conductor transmission line 120 ft long (36.6 meters) and measurement capability down to about 1 MHz. The aluminum-pipe line is not tunable; it is terminated by a shorting bar of the same pipe stock, or by two 24-inch open-end extensions which compensate for the electrical length of the shorting bar. A large aluminum plate has also been used as a shorting device, with no change in performance.

Although spacers can be used with this transmission line, if desired, generally they will not be needed, because the spacing is maintained at approximately 40 inches by placement of the support posts. (With this line spacing, the characteristic impedance of the line should be 359Ω in air.) These posts are made of 8-ft oak poles--with metal

* The effect on conductor capacitance of a thin layer of insulation is negligible, as may be seen from the development of Ref. 9.

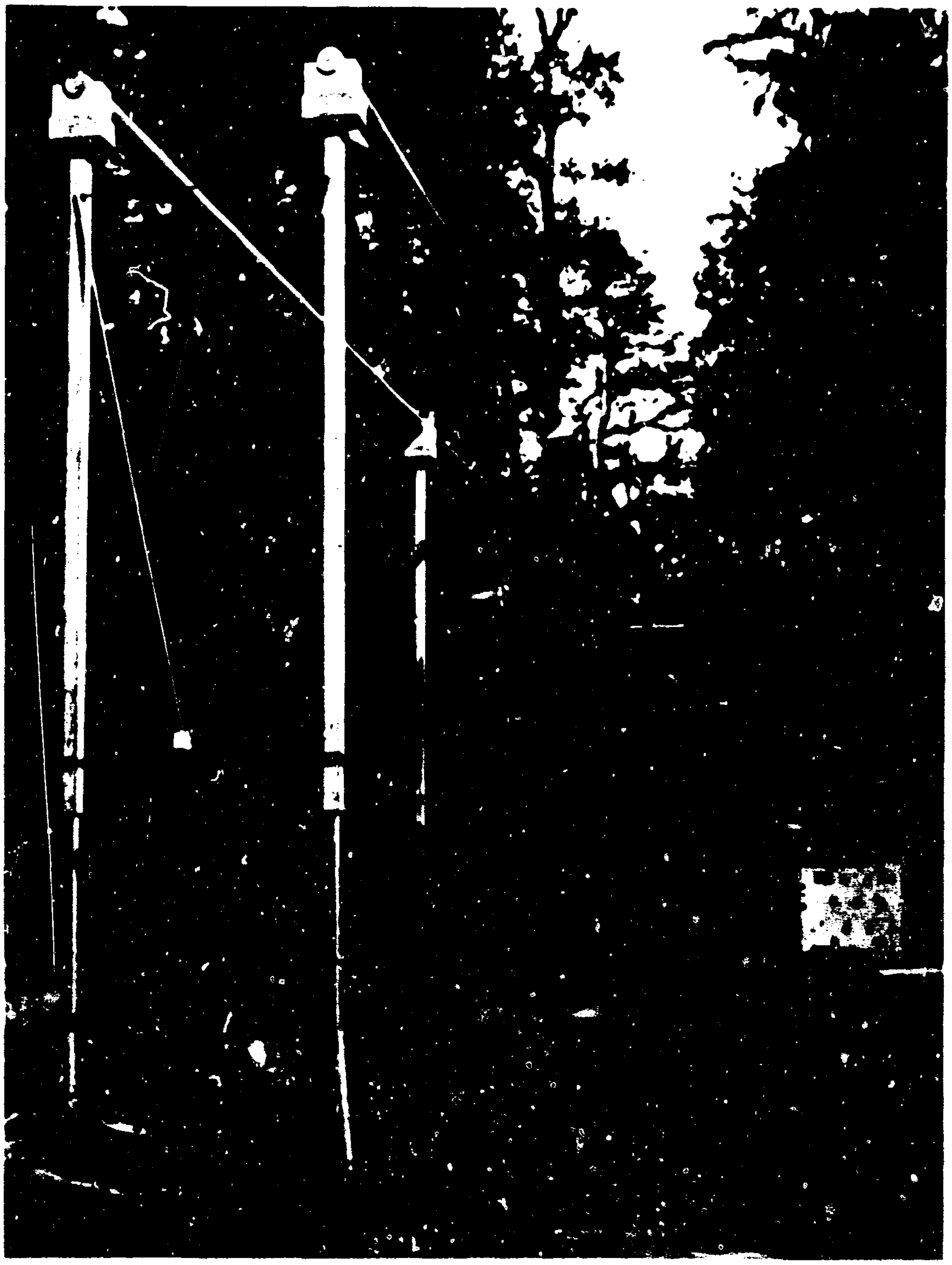

FIG. 8 HF OWL SHOWING TOROID BALUN WITH SPREADER EXTENSIONS

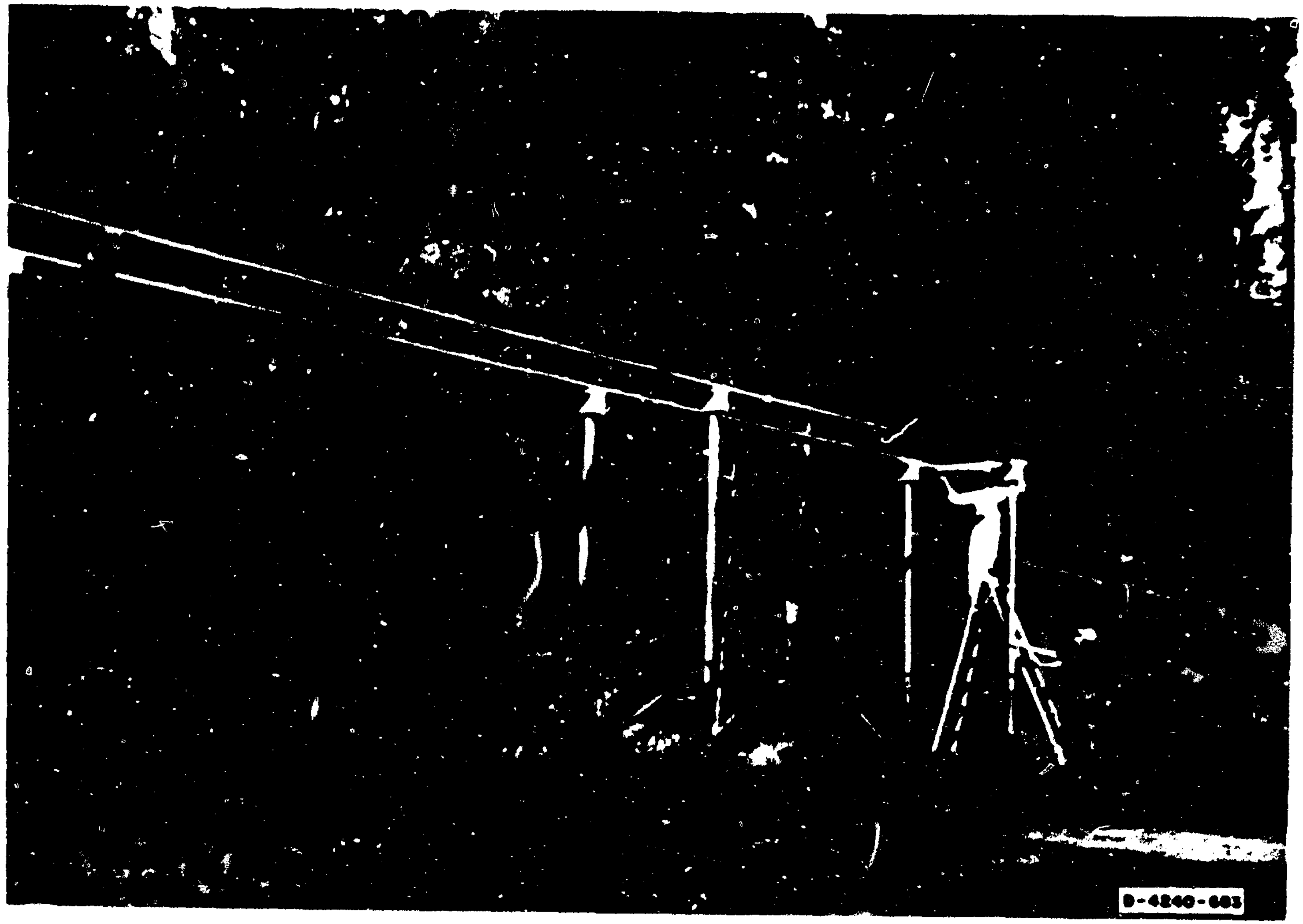

FIG. 9 PLACEMENT OF SHORTING BAR AT HF OWL TERMINATION

points that can be driven 2 ft into the earth--over which fit plywood box sleeves with clamps for height adjustment. The sleeves, 8 ft long, support styrofoam yokes upon which rest the aluminum pipes All porous materials were treated with moisture-resistant sealer paint. The maximum adjustment height of the support posts is about 15 ft. For measurements at greater heights, the pipes can be spread with styrofoam spacers and hoisted by ropes on tree-held pulleys.

For connection between the balanced aluminum line and the impedance bridge, several toroidal baluns were wound. The toroids held a fairly constant impedance transformation ratio of about $0.95\angle{-18^\circ}$ over the range 1 to 30 MHz. The upper limit of the operating frequency range of the large aluminum transmission line has been estimated at 30 MHz.

Use of this large aluminum-pipe line with support posts presupposes that a volume of fairly homogeneous foliage about 10 by 50 by 10 meters can be found, over nearly level earth. If the transmission line is suspended by ropes, only a group of tall trees is required.

C. PARALLEL-PLATE CAPACITOR

A large capacitor having parallel plates 4 by 7.5 ft and a "tapered-feed" input funnel, as shown in Fig. 10 was fabricated, with parallel plates 1 ft apart and input via coax from a General Radio bridge (Model 1606-A or 1601). This capacitor can be used to "sandwich" (standing on its edge) a volume of living foliage trimmed in a hedge shape. Bridge measurements of this foliage dielectric, taken together with measurements of air dielectric under similar conditions of geometry and relative humidity provide the electrical properties of the foliage as developed in Sec. [illegible]-C. Cut foliage packed between the capacitor plates has been measured in the same way. In either case, the result is a value for the effective complex dielectric constant of the foliage/air mixture filling the capacitor.

FIG. 10 PARALLEL-PLATE CAPACITOR, SHOWING TAPERED INPUT

This capacitor is not easily handled: Its weight (up to 100 lb) and bulk are impediments to field use. But since a capacitor has a very broad frequency range (VLF to HF), we have considered it as a means for providing continuity with other (narrow-range) foliage sensors.

IV ELECTRICAL PROPERTIES OF FOLIAGE

A. GENERAL

Measurements have been made at 30, 50, and 75 MHz with the brass VHF line. We plan to extend the frequency range of the data as far above and below this range as the equipment will allow. This probably means 20 to 100 MHz for the VHF OWL, because it becomes too lossy at higher frequencies and cannot be easily tuned at lower frequencies. The HF OWL has been used to cover the 1-to-25 MHz range.

Measurements have consisted of:

(1) VHF Transmission Line (3-inch spacing)

(a) Short-circuit resonance data at 3/4- and 5/4-wavelength positions, to provide $\lambda_m(\epsilon_r)$ and impedance, and hence α if Z_o is known.

(b) Impedance measurements at a position about 0.06 λ_m to 0.19 λ_m beyond the resonant length, where the open-circuit and short-circuit impedances are well balanced (that is, the sensing volume of the line is similar for both terminations). These measurements of Z_{oc} and Z_{sc} provide data for the computation of Z_o and for an independent determination of α and β.

(2) HF Transmission Line (40-inch spacing)

Measurements similar to those described in (1b) above have been made. Since the line is not tunable, its resonant length is estimated by probing the standing-wave pattern, and the test frequency is adjusted slightly to give an optimum number of partial wavelengths on the line.

(3) Large Parallel-Plate Capacitor

Several measurements have been made on loosely-packed cut foliage (a mixture of avocado, pine and apple). The boughs had been cut for about two weeks when tested. Later a test was made on living maple, using a larger capacitor built in the Hoh Forest, Olympic National Park, Washington.

Curves of α_n, β_n, and ϵ'_{rn}, separated into ϵ_{rn} and ϵ''_n, loss tangent δ_n, conductivity σ_n, and $\Gamma_n = (\alpha_n + j\beta_n)$ can be presented as functions of

frequency when enough data have been taken over a band of frequencies at the same site.* The meaning of the various parameters is developed in Sec. II and VI. Vertical bars are used to indicate spread in their values, while a symbol is placed at the mean position. The maximum and minimum limits are probably most significant aspects for these data.

As discussed in detail in Sec. VI, the upper and lower limits for loss-related parameters (α_n, σ_n, δ_n) are obtained from two distinct, though similar, methods of analysis. The larger values result when normalization to air data is made in full. The lower values are somewhat "forced" in an effort to minimize the effect of axial inhomogeneity of the sample medium about the OWL. This is done by neglecting the argument of Z_o (for the OWL in the sample) the second time it appears in the normalization sequence. This dual analysis was applied to all data taken after August 1965. The limits shown for earlier data represent only the spread in series of measurements for which no normalization was made. It should be noted that normalization of these early results, if it were possible, would increase their magnitudes by about a factor of two.

The values obtained from measurements in foliage are to be compared with their counterparts obtained from control measurements in air. A normalization procedure for relating sample measurements to air measurements is presented in Sec. VI. So far, conditions under control have been line length (in wavelengths), frequency, dielectric spacer positions, and height above earth. We have also attempted to "control" air humidity and temperature by suitable scheduling of measurements, but preliminary results indicate that these last variables have little effect on measurements.

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* The subscript n is used to indicate values that have been normalized to air data.

B. MEASUREMENTS OF ELECTRICAL PROPERTIES OF FOLIAGE IN CALIFORNIA

1. Living Foliage

Values of α and ϵ_r have been obtained for two living foliage samples and two cut samples in California. Table I shows values obtained by using the VHF transmission line, for effective attenuation rate α, conductivity σ, and relative dielectric constant ϵ_r, in dense poison oak with vines and in relatively less dense fern-like vegetation. Control values obtained at the same time are also shown. The data were obtained in June and July, 1965. The Fiberglas case was not used.

Table I

α, σ AND ϵ_r IN POISON OAK AND FERNS AT 50 MHz

Living Vegetation	α (neper/meter)	σ (mho/meter)	ϵ_r
Poison oak and vines	40×10^{-3}	21×10^{-5}	1.1
Control	3.5×10^{-3}	1.8×10^{-5}	1.01
Fern*	$(19 - 26) \times 10^{-3}$	$(10 - 15) \times 10^{-5}$	1.1
Control	2×10^{-3}	1×10^{-5}	1.01

* These were less dense than the vegetation containing the poison oak.

2. Time Variations of the Electrical Properties of Fresh-Cut Oak Boughs

Oak boughs cut at SRI on 21 July 1965 were used for an experiment with the VHF line operated at 50 MHz. Control data were taken prior to piling oak limbs about the transmission line (see Fig. 11). Measurements of the newly cut foliage were first made at 1300 local time on 23 July. Subsequently, measurements with the transmission line in the pile were made at 0900 local time 26 through 30 July, and an hourly series of tests was made on 2 August and again on 4 August to find whether humidity effects were evident. Results of these last measurements are shown in Fig. 12. Concurrently, a sample oak limb was tested

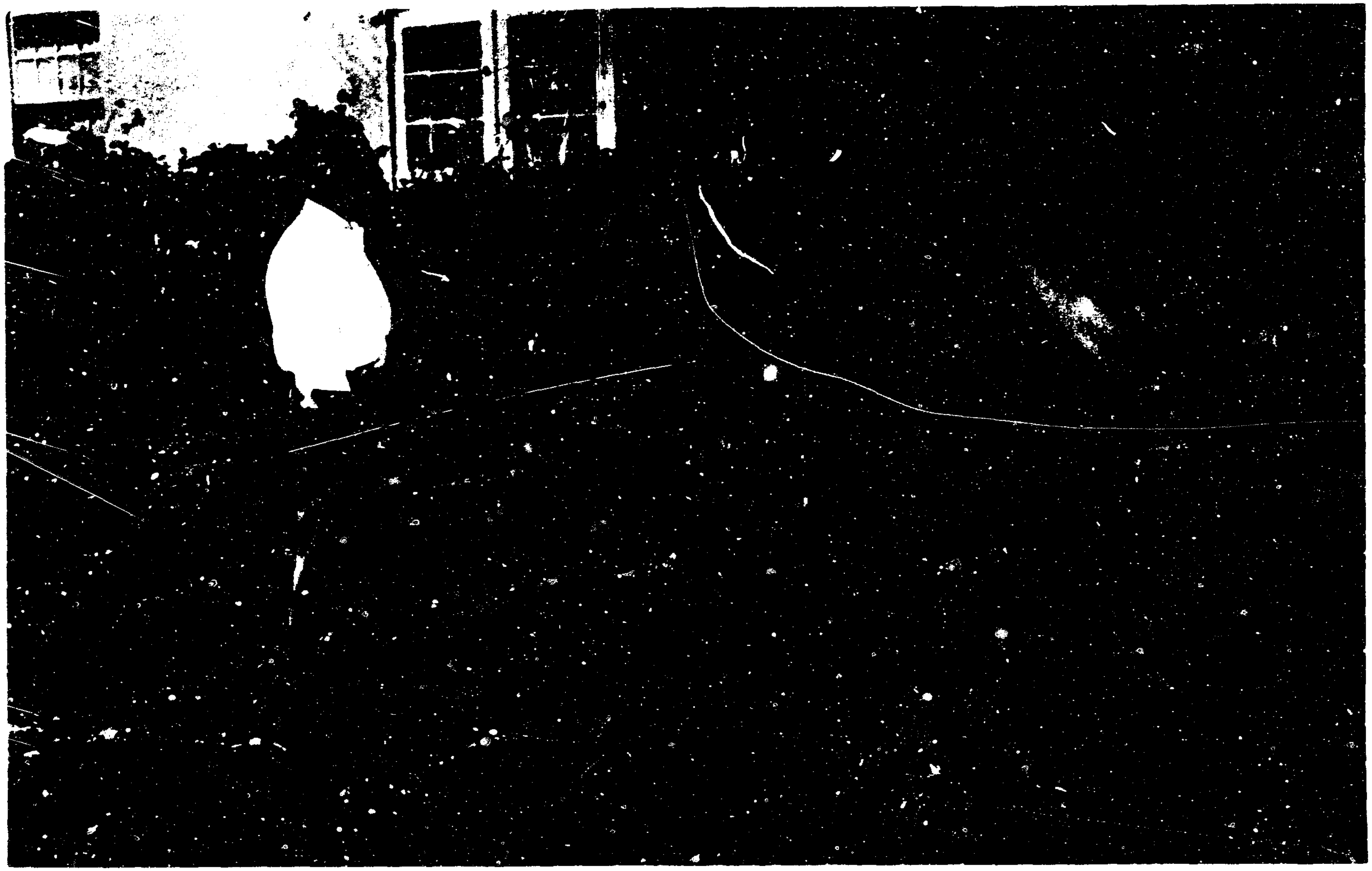

FIG. 11 CUT-OAK EXPERIMENT

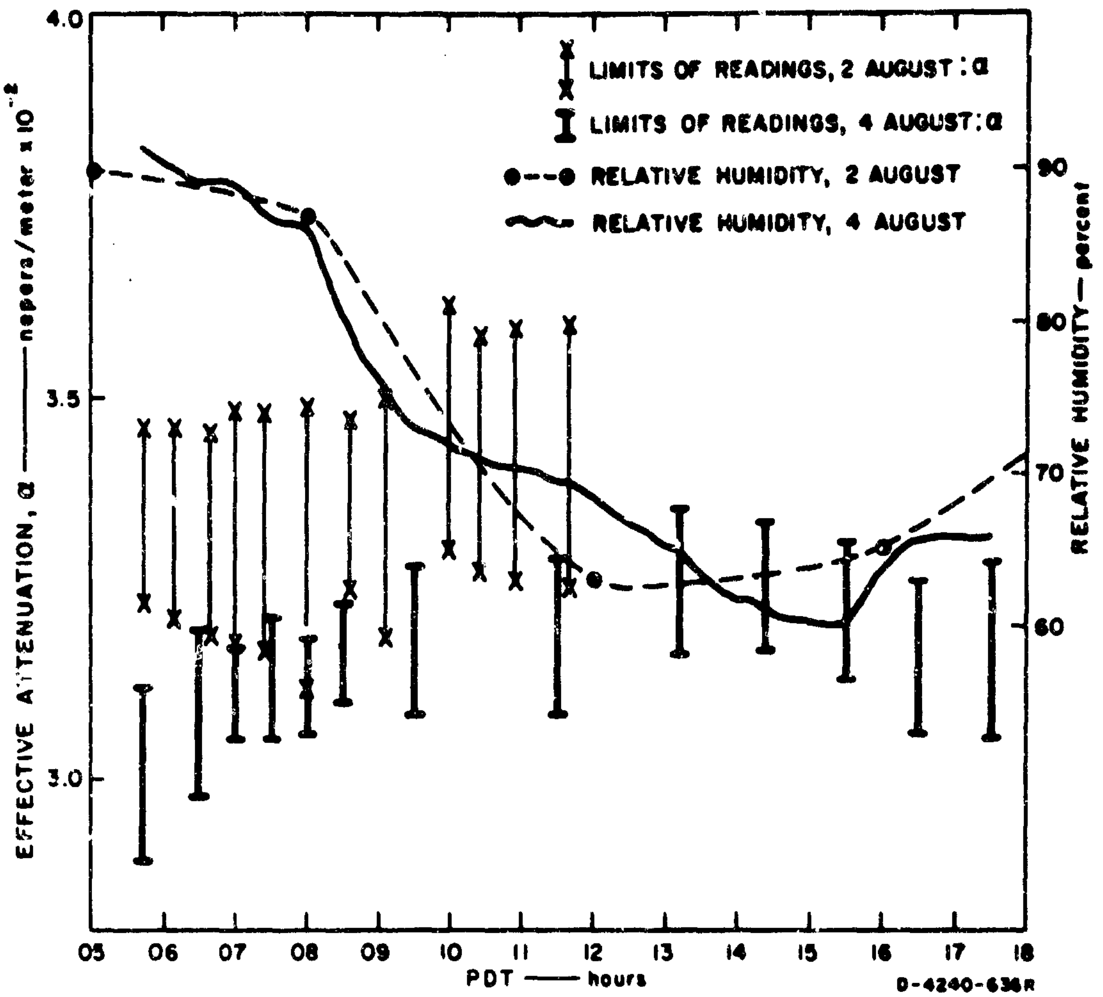

FIG. 12 VARIATION IN AIR HUMIDITY AND ATTENUATION IN CUT OAK FOLIAGE AFTER DRYING PERIOD

in the laboratory, where values of its dc conductivity were obtained at the same times the foliage measurements were made.

The results of the two experiments are summarized in Fig. 13. Here, α and ϵ_r are given just as measured. Control values were obtained only for the first day, since it was impossible to remove the transmission line from the pile without voiding the experiment. The Fiberglas case was not used with the OWL.

The values of α shown for the oak-limb laboratory sample were generated by assuming that the volume of foliage relative to air in

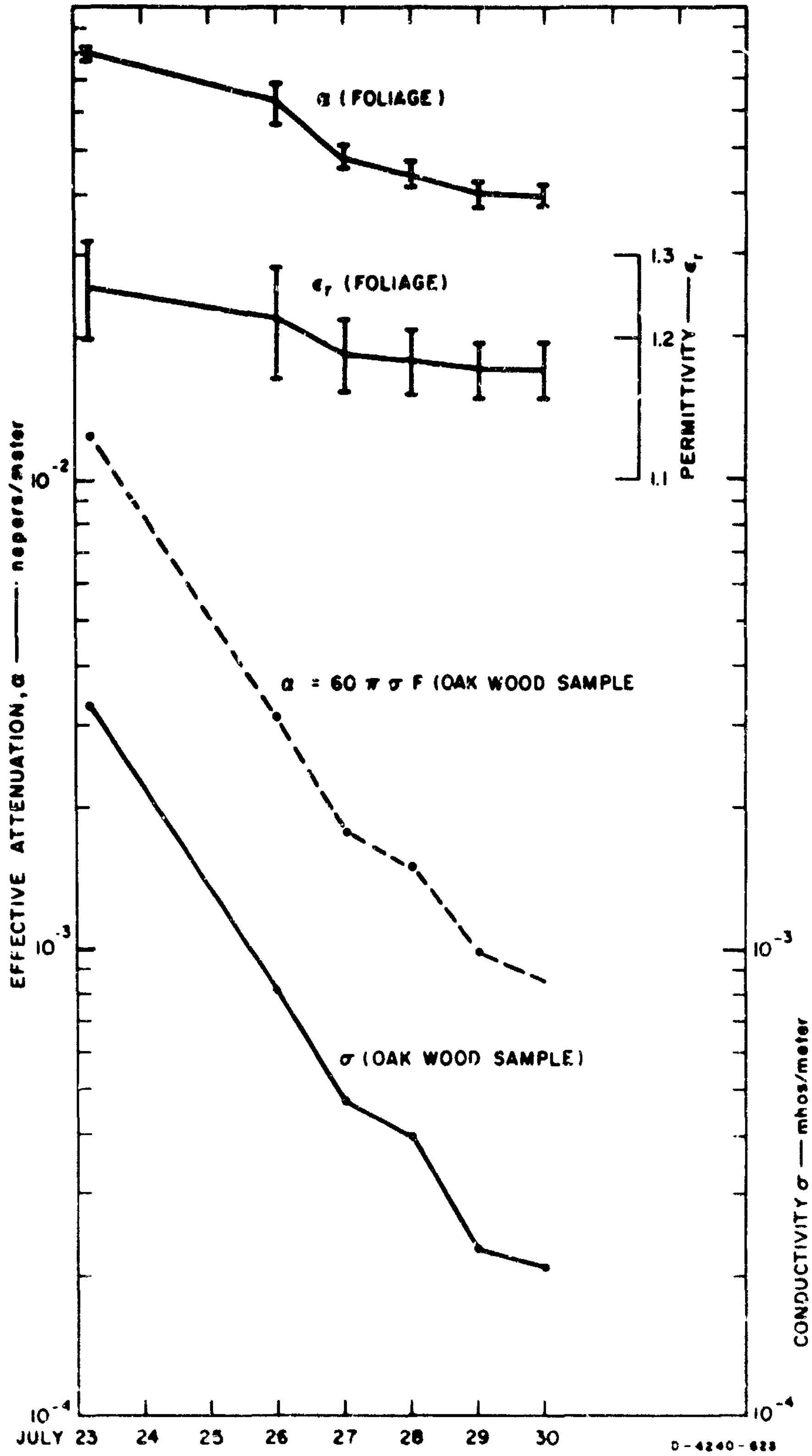

FIG. 13 VARIATION IN COMPLEX DIELECTRIC CONSTANT WITH DRYING OF CUT OAK

the brush pile was $F = 10^{-2}$ and by using the equations of Sec. II to estimate an attenuation, α, which might correspond (for the brush pile) to the σ obtained for the oak limb. No attempt was made to measure the conductivity of the oak limb at VHF, but other researchers[10] have obtained similar magnitudes for oak at HF to those we found at dc. The actual conductivities measured from the oak-limb sample are also given in Fig. 13.

Note that the time variations for the transmission-line values and those for the dc conductivities are similar. The generated values of α for the oak limb are lower than those actually measured in the brush pile. This may be expected, for the brushpile contained many leaves, with higher conductivities than the woody stems, which were not included in the estimate.

3. A Second Test Series with Cut Foliage

A similar cut-foliage test was undertaken in late August, 1965, with 75-MHz measurements also being made. The cuttings, from avocado, pine, apple, mahonia, and plum trees, were packed more densely than in the first pile of cuttings (see Fig. 14). In this instance, the density of the brush was so great that the VHF transmission line was highly detuned when measurements were first attempted on 26 August (no Fiberglas casing was used). We decided to wait over the weekend for the foliage to dry partially. We estimated an ϵ_r of about 4 on 26 August.

On beginning the measurements 30 August, we found it impossible to tune the line by moving the trombone section, since this meant extending it outside the pile of foliage, thereby producing rather meaningless data. Thus, the line was left at a fixed length equal to the length of the foliage pile, and only Z_{oc} and Z_{sc} impedances were read. Values of α and ϵ_r computed from the impedances are shown as a function of time in Fig. 15. Since only one method of obtaining data was used, no spread in values is shown, except for a special test on 1 September, when the line length was varied slightly to give different readings. The fluctuations in α and ϵ_r seen following the initial fast-drying period (first two or three days) both in these data and in those of Sec. IV-B-2 seemed

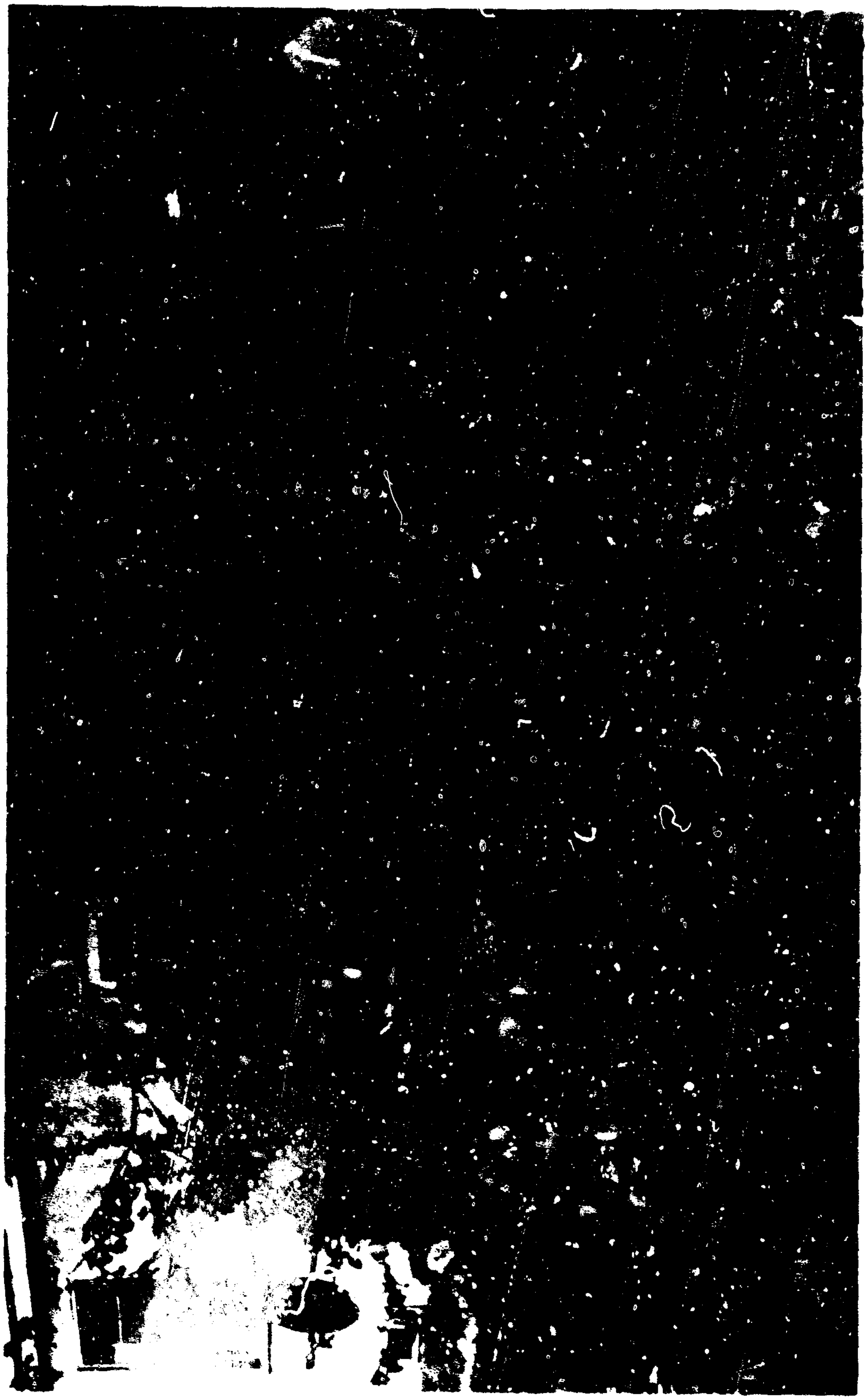

FIG. 14 MIXED CUT FOLIAGE SAMPLE

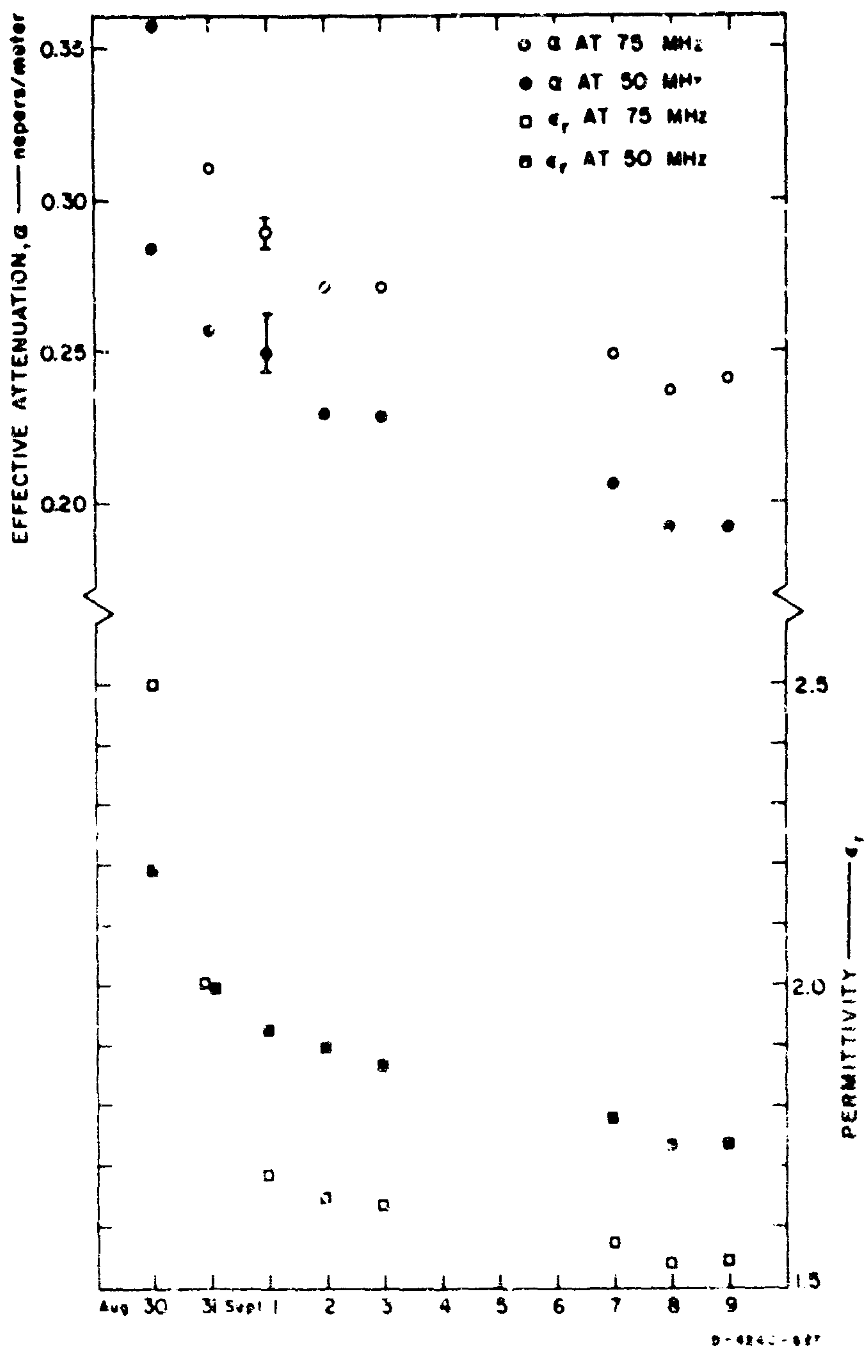

FIG. 15 VARIATION IN COMPLEX DIELECTRIC CONSTANT
WITH DRYING OF MIXED CUT FOLIAGE

unrelated to air humidity, unless there is a 12-hour lag in the response of the piled cuttings to humidity changes.

The high values for ϵ_r (75 MHz) in Fig. 15 may indicate that the medium was still detuning the transmission line so much to allow satisfactory measurement at that frequency on 30 and 31 August. On the remaining days, ϵ_r at both frequencies varied in a manner consistent with slow evaporation of water.

Assuming that water accounted for most of the material in the cut-foliage pile, we were able to estimate its fractional volume F by reversing the development of Sec. II-D. For dielectric slabs in parallel, we obtained $F_{max} = 0.02$, $F_{min} = 0.01$, hence a change of 2:1 as the foliage dried. Similarly, assuming dielectric slabs in series, we found $F_{max} = 0.6$, $F_{min} = 0.4$, or a change of 3:2. These are the upper and lower bounds on the dielectric behavior of the pile. The two cases indicate that σ_v was between 0.03 and 0.9 mho/meter for the intrinsic conductivity of the foliage.

4. Parallel-Plate Capacitor Testing

Samples of foliage from the second brush pile (Sec. IV-B-3) were packed loosely between the parallel plates of an aluminum capacitor (4 by 3.5 ft by 4 inches, with tapered feed). Species used were avocado, pine, and plum. These had been cut for about two weeks when measured.

Impedances were read with a General Radio Model 1601 bridge (through a remote extension coax) at 50, 75, and 100 MHz with the capacitor both horizontal and vertical (standing on one edge). The position of the capacitor did not significantly affect the results obtained.

The accuracy of these measurements was poor, largely because impedances were transformed with a Smith reactance slide rule. Values obtained at the three frequencies were similar: ϵ_r was about 1.2 and σ was about 7.5×10^{-4} mho/meter; these are reasonable orders of magnitude. A more accurate capacitor experiment was designed for use in the field.

C. HOH FOREST FIELD TRIALS

1. Sitka Spruce

A field site was operated in September and October 1965 in the Hoh rain forest in the Olympic National Park. The bus used as laboratory/living quarters is shown in Fig. 16 beside the HF OWL. Measurements were made in a Sitka spruce thicket of high-density (1 to 1.5 ft between stems, no visibility) growth, with the VHF transmission line 6 ft high. (See photographs, Figs. 17 and 18.) The VHF OWL was left in its Fiberglas case. Surprisingly, the rain forest was relatively dry, as indicated by the range of α values obtained (see Fig. 19); dust could be raised on the forest floor by scuffing the moss covering with a shoe. Park authorities indicated that rainfall had been only 0.75 inches in July and in August, with even less prior to the measurements in September. Normal rainfall for each of these months averages 4-6 inches.

From measurements made before and after a 12-hour rain on 29 September we noted a significant difference between dry and wet climatic conditions (thus, presumably between drier, and more moist, living plant tissue) but found no difference between wet (24 hours after rain began) and dry (sun-dried: 30 hours after rain) conditions of the surfaces of needles and branches.

Comparison of these results (Fig. 19) with those given in Table I for foliage growing near Menlo Park, California indicates that, although the spruce grove in the rain forest was considerably more dense than the California foliage tested, its attenuation was somewhat less. These results may reflect difference between species, between periods in the growing season (July in California, September in the rain forest), or in biological adaptation to climate. Clearly, more cataloguing of foliage properties must be done before such results can be interpreted fully.

2. Vine Maple

The VHF transmission line was used as a sensor in sparse vine maple at two sites in the Hoh Valley (see photographs, Figs. 20, 21, and 22) on 6 October, a sunny day following three days of rain, and again on 14 October, a rainy day. The latter setup was in a slightly more dense

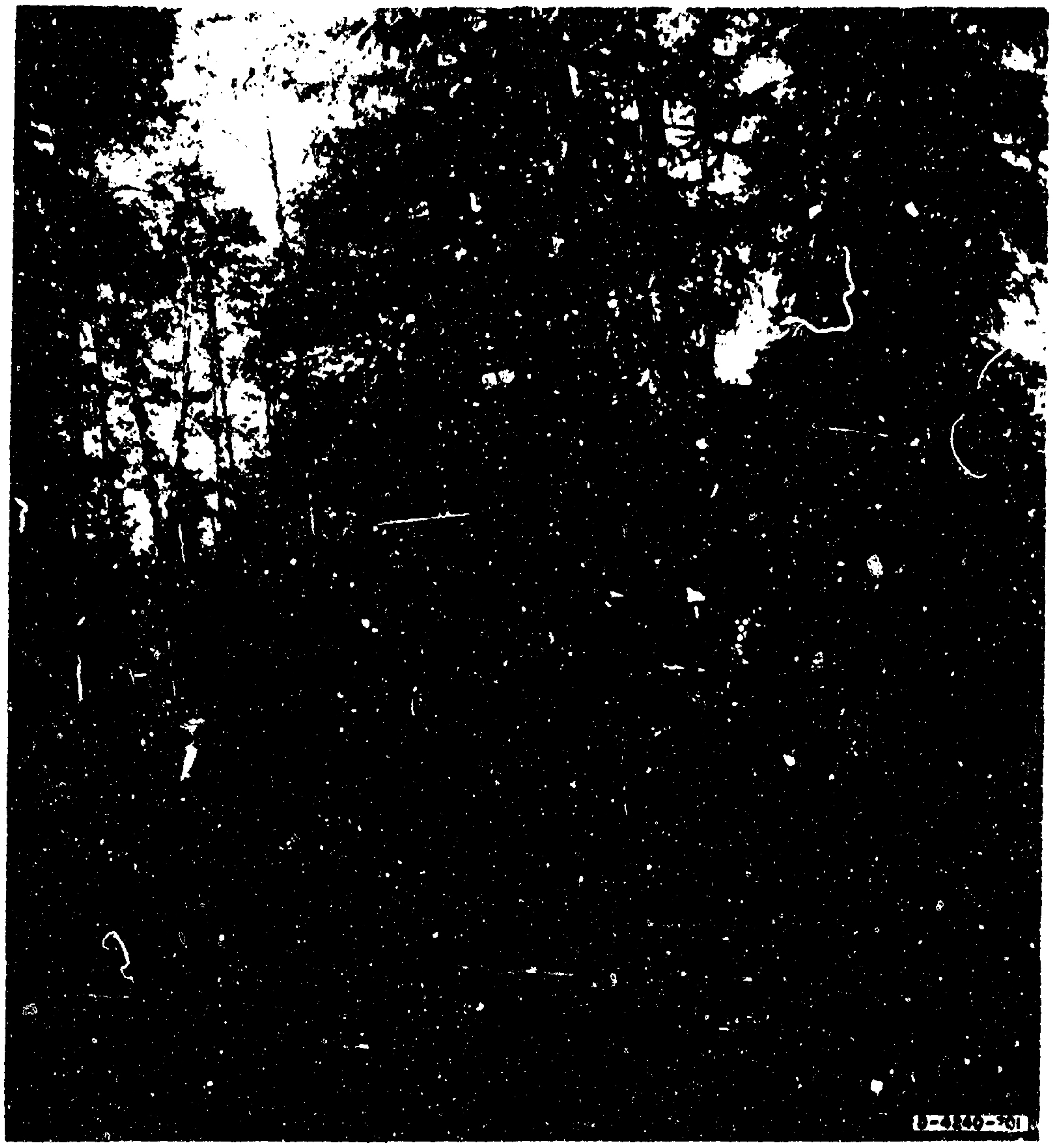

FIG. 16 BASE CAMP IN THE HOH VALLEY

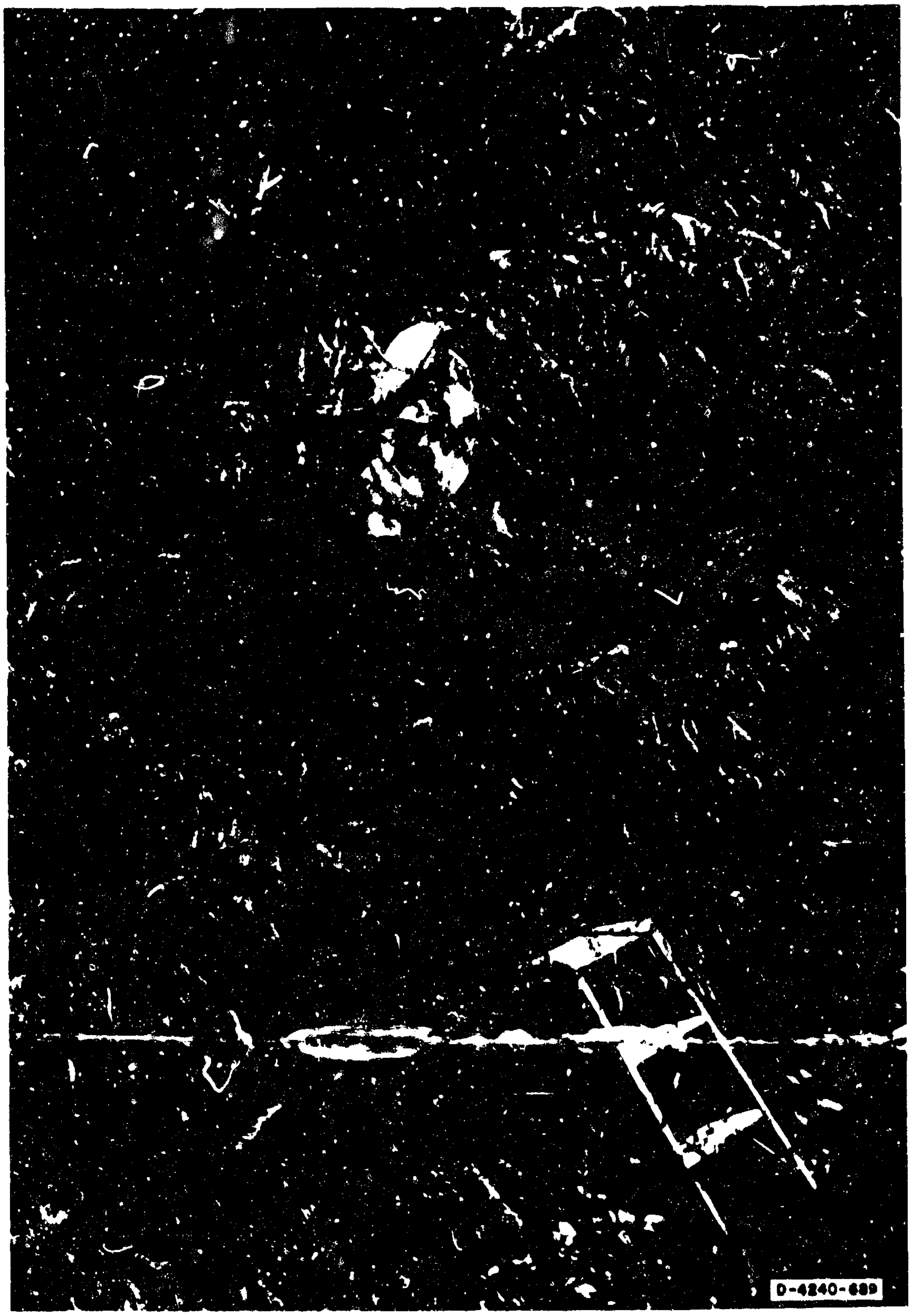

FIG. 17 VHF OWL IN SITKA SPRUCE, HOH FOREST

FIG. 18 CONTROL EXPERIMENT (Sitka spruce in background)

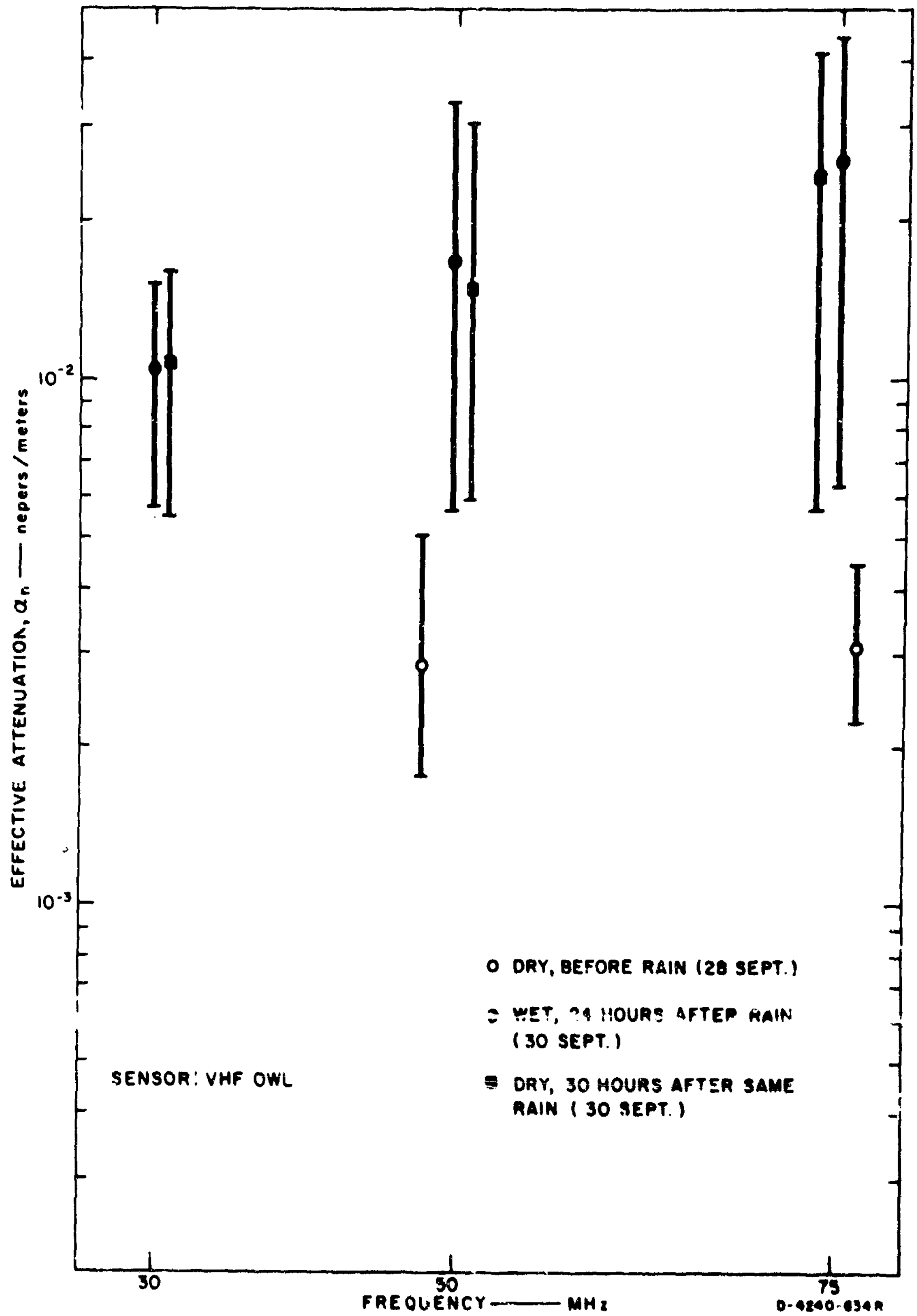

FIG. 19 VHF ATTENUATION IN SITKA SPRUCE, HOH FOREST

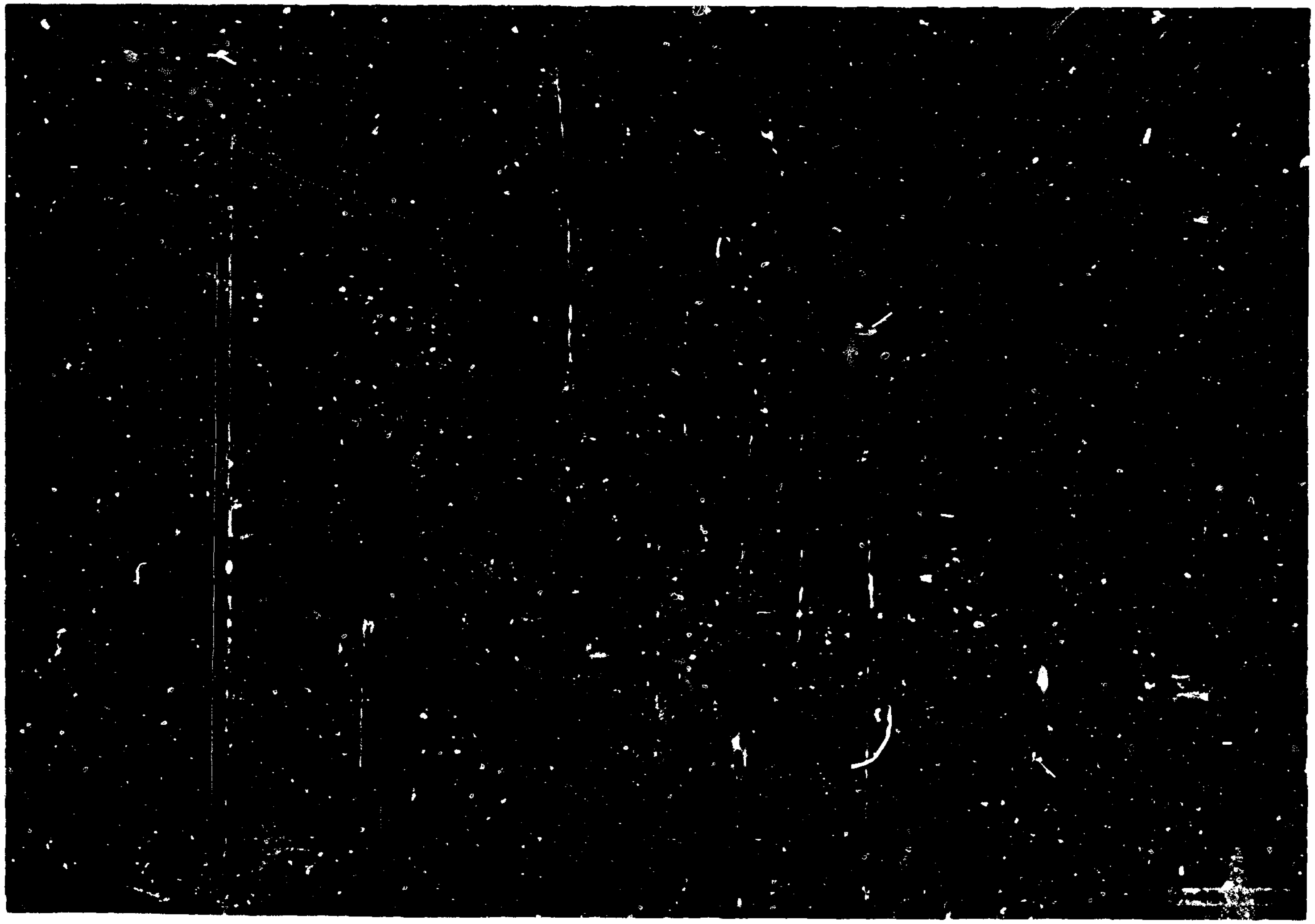

FIG. 20 VHF OWL IN VINE MAPLE, SITE I, HOH FOREST

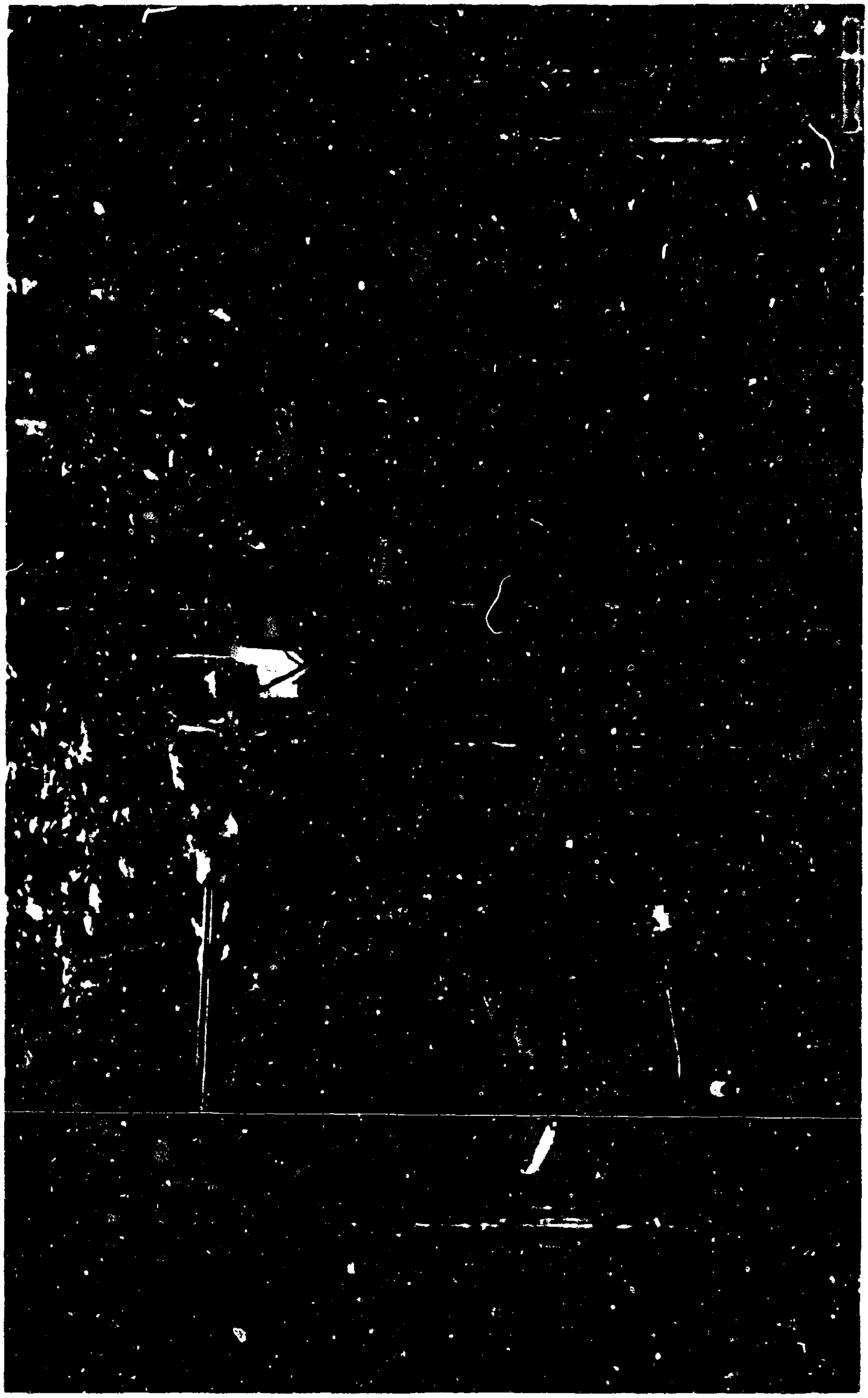

FIG. 21 ADJUSTMENT OF VHF CONDUCTOR LENGTH AT VINE MAPLE SITE II, HOH FOREST

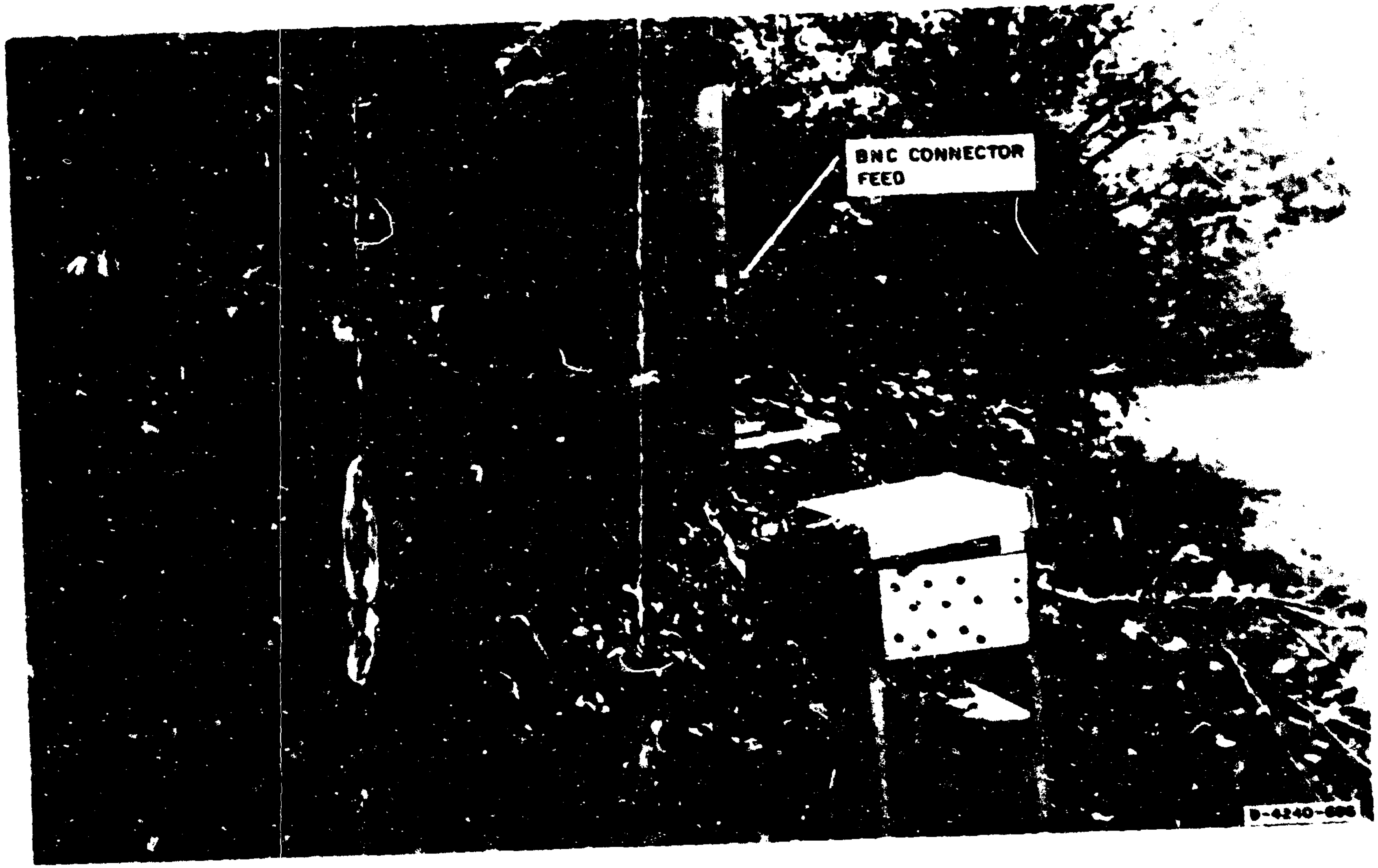

FIG. 22 CAPACITOR, INPUT END, VINE MAPLE SITE II

growth of maple that was subsequently tested for electrical properties with a large parallel-plate capacitor. At both sites, the VHF OWL was left in its Fiberglas case.

The results at the two sites about 1.5 miles apart in the Hoh Valley are compared in Fig. 23. Although the growth at Site II was visibly the more dense, and even though the measurements there were taken during a rain when foliage was thoroughly wet on the outside, attenuation at Site II was significantly lower than at Site I, which, though dry, was recovering from the effects of a three-day rain.

Measurements made October 15 at Site II with a large parallel-plate capacitor--"foliage sandwich"--are shown in Fig. 24. The capacitor was 10 by 4 ft by 1 ft wide, supported on sawhorses at approximately the same position occurpied by the VHF OWL on 14 October. Obviously there was a problem in that the capacitor was quite lossy even when operated with air as a dielectric (we found that its Q was never better than 22). Whatever the cause, conductivities obtained from the capacitor measurements were unreasonably high at frequencies above 10 MHz and do not compare well with conductivities obtained from VHF transmission line measurements at Site II.

3. Red Alder

Both transmission lines were set up in a dense (1 to 3 ft between stems, complete shade) red alder thicket about 20 yards from the Hoh River (photographs of the site are shown in Figs. 25 through 30). The instrument height was 12 to 16 ft for the HF line. The height of the VHF line was varied from 6 to 12 ft on several occasions, without significant change in the values of attenuation obtained (see Fig. 31). The VHF OWL was left in its Fiberglas case.

The VHF line was always set up within about 10 ft of the HF line, so results could be compared, as in Fig. 32. The frequency ranges of the two apparatus overlap at 30 MHz.

Because the HF line is not physically tunable, experimental frequencies were chosen to fit about $(2n + 1)(\lambda_m/8)$ wavelengths into the 18.9 meters of line. Under these conditions, measurements of short-circuit and open-circuit impedances included approximately the same active sensing volume.

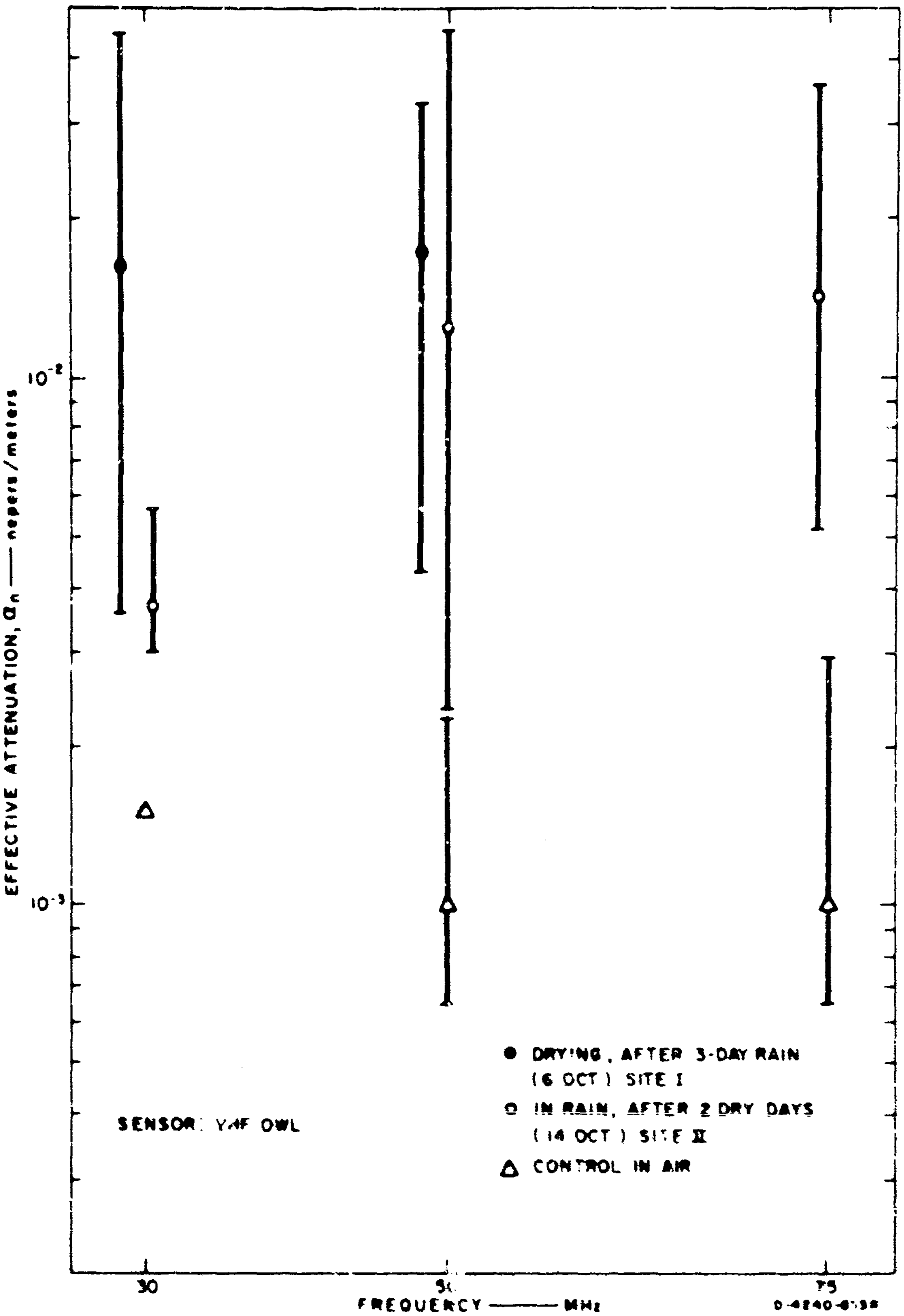

FIG. 23 VHF ATTENUATION IN VINE MAPLE AT TWO SITES, HOH FOREST

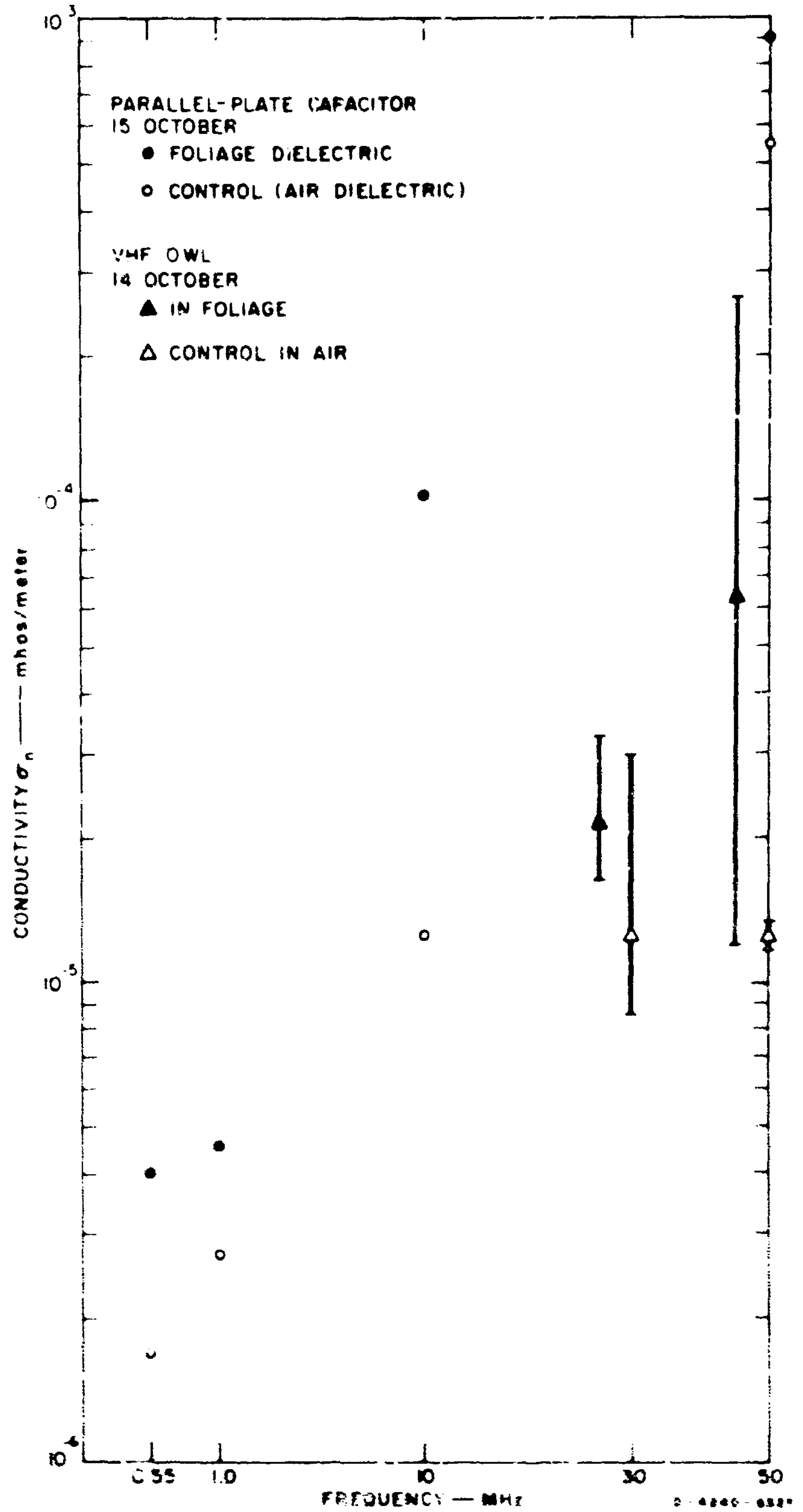

FIG. 24 COMPARISON OF CAPACITOR AND VHF OWL AT VINE MAPLE SITE II

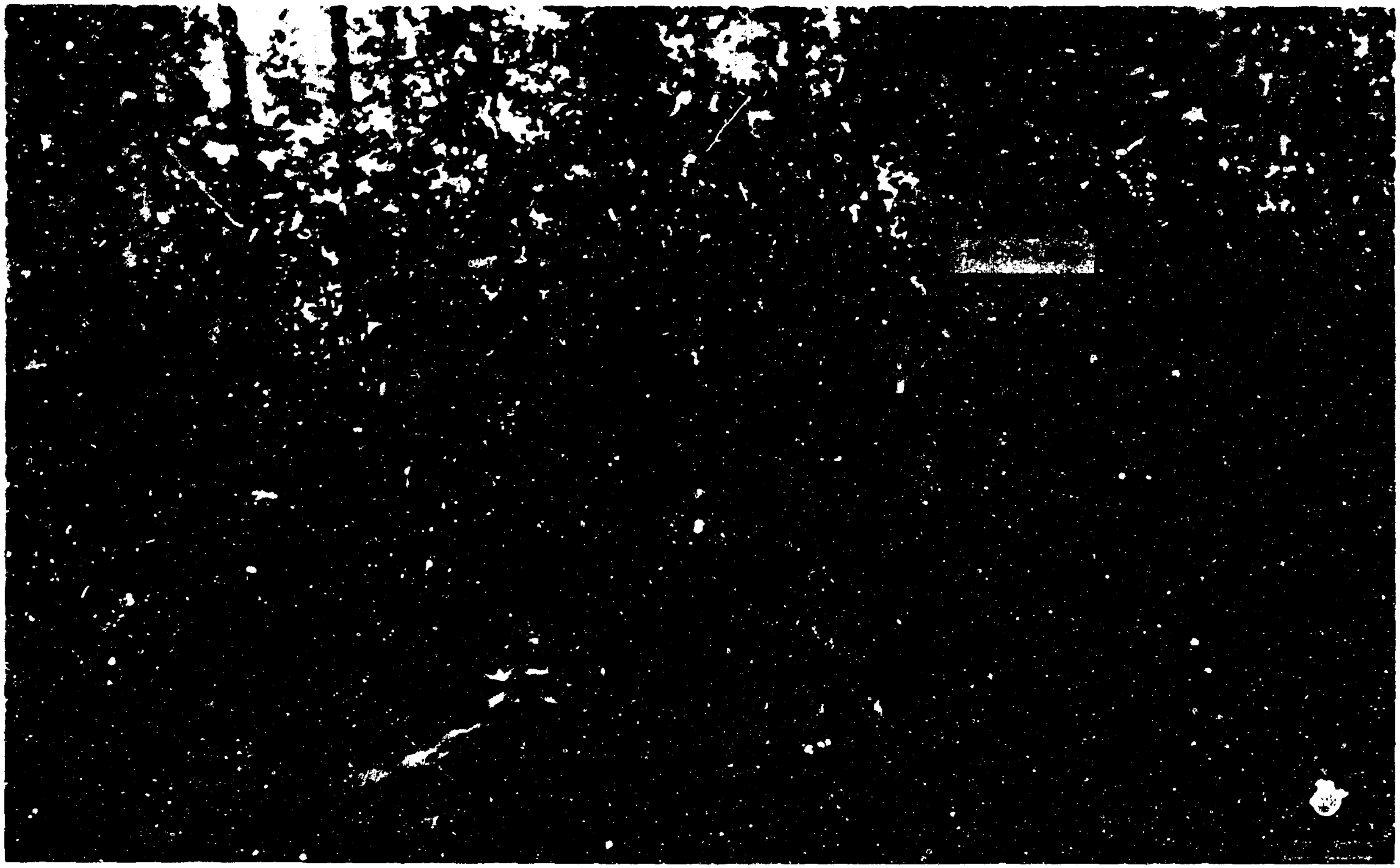

FIG. 25 NORTH SIDE OF RED ALDER GROVE, HOH FOREST (HF Line Visible Across Center)

FIG. 25 SOUTH SIDE OF RED ALDER GROVE

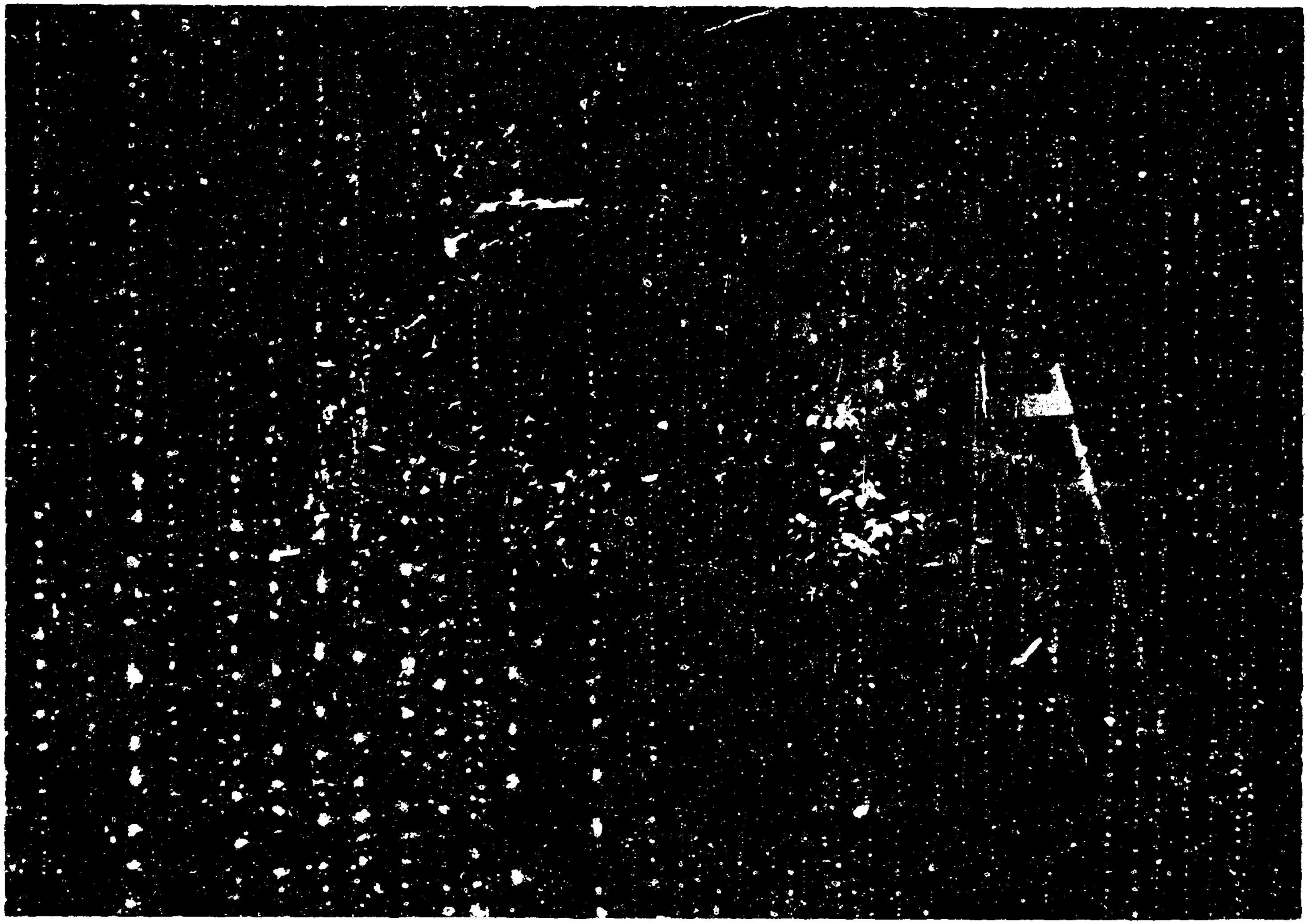

FIG. 27 ALDER GROVE FROM SOUTHEAST, SHOWING HF LINE

FIG. 28 TERMINAL END, HF OWL IN RED ALDER

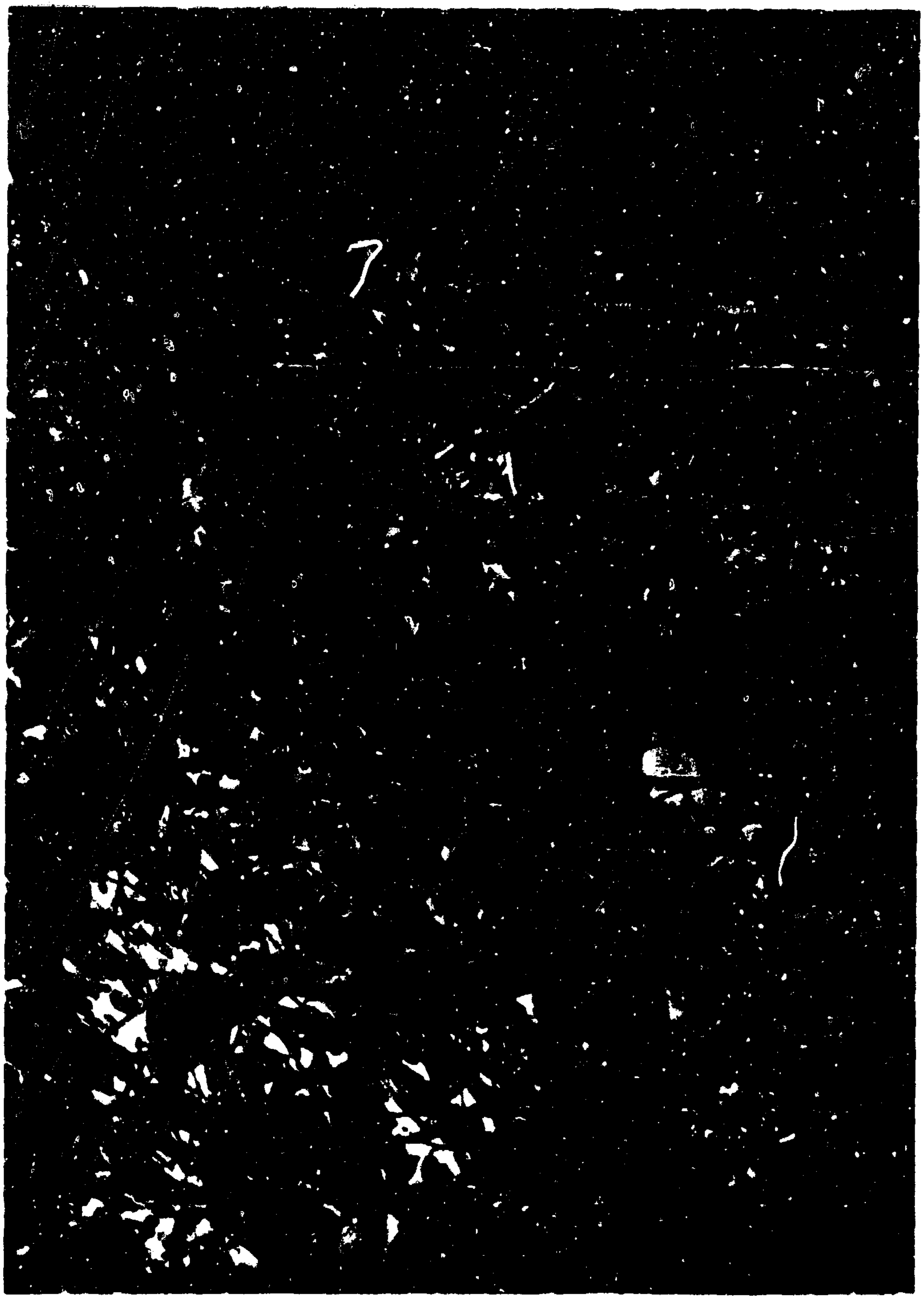

FIG. 29 HF LINE CONDUCTOR IN RED ALDER FOLIAGE

FIG. 30 DISMANTLING HF OWL IN RED ALDER GROVE

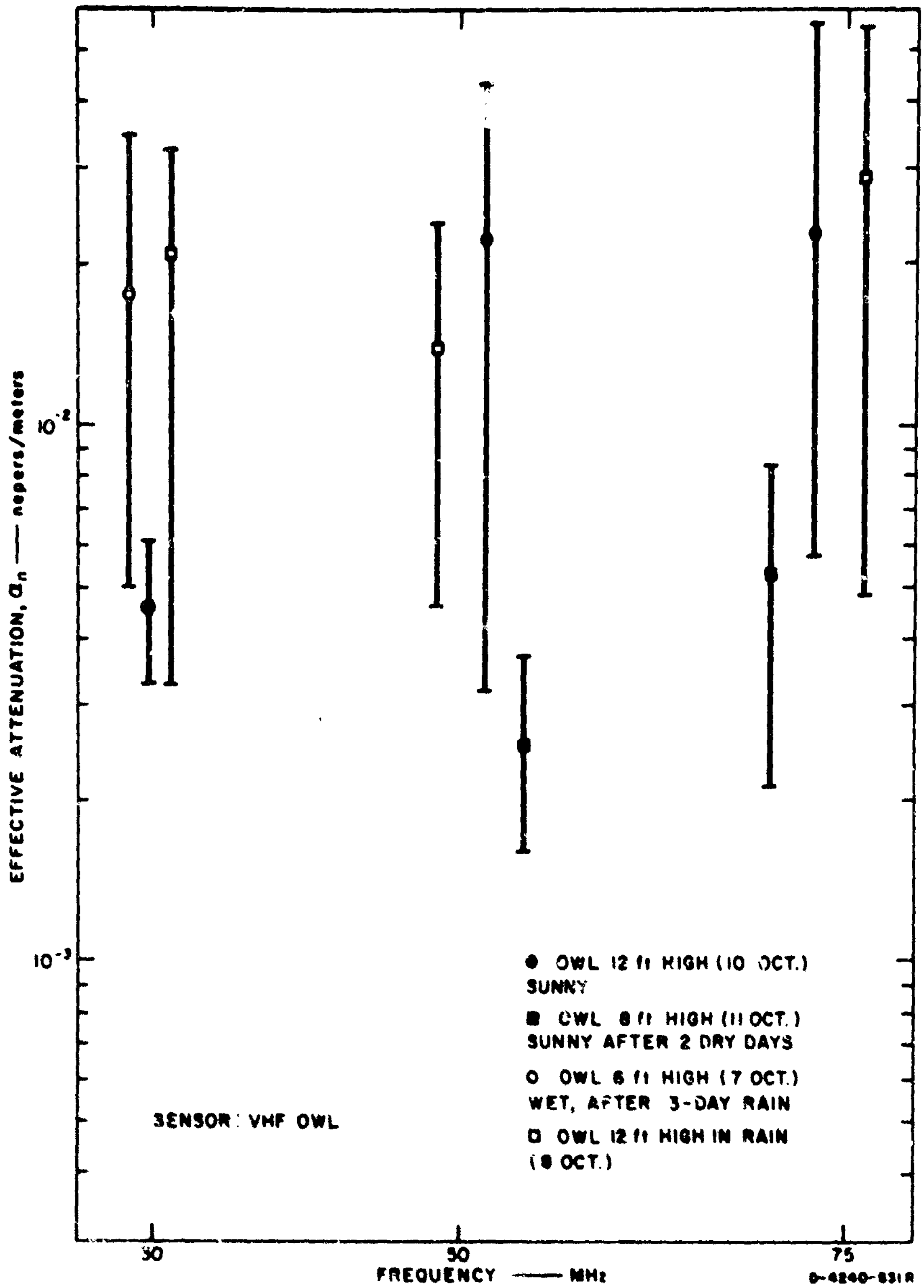

FIG. 31 VHF ATTENUATION IN RED ALDER, HCH FOREST

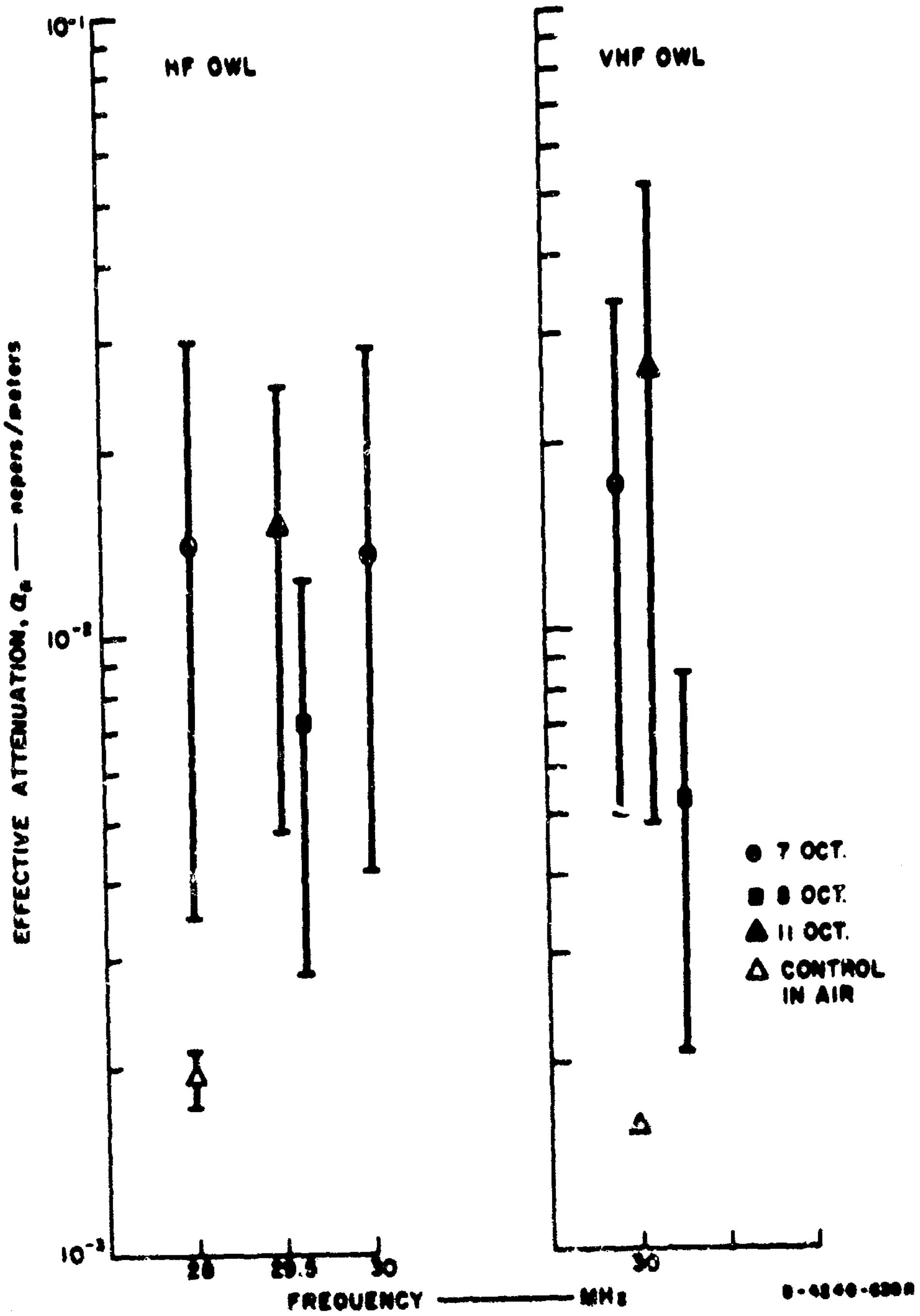

FIG. 32 COMPARISON OF HF AND VHF LINES IN RED ALDER

Attenuation measured with the HF line in red alder on several different days is shown in Fig. 33. From the behavior of the control measurements with frequency, one may infer that the large aluminum line becomes too lossy to be used as a foliage sensor at frequencies much above 30 MHz.

Although the alder is deciduous, it was still quite green in mid-October. Here again, however, the range of α values obtained was lower than that found in California in July. The alder may thus have already entered its dormant season.

The data of Fig. 33 show no clearly defined relationship to rainfall conditions, beyond a tendency toward higher loss on 6 October. This cannot be definitely accounted for, but we surmise that the alder grove was so saturated by flooding of the Hoh River 4 to 6 October (to a maximum depth of 14 inches at the terminal end of the transmission line) that it did not dry out in the vicinity of the HF line during the week of testing (6 to 13 October).

A significant aspect of the data shown in Fig. 33 is the variation of control values with frequency. Although the HF OWL became more lossy as the operating frequency was increased toward an upper limit of usefulness between 30 and 35 MHz, this phenomenon did not affect foliage measurements. (The highest frequency at which control data were taken with the HF OWL was 28 MHz.) Apparently, the OWL remained an accurate tool as long as the α_n of the medium surrounding it was at least twice as great as the α obtained with the OWL in air.

4. Summary of Hoh Forest Field Trials

With the exception of the parallel-plate capacitor, we feel that the reliability and usefulness of all the equipment tested at the Olympic National Park is quite satisfactory. The operation of the equipment was not affected by heavy rainfall, and the two transmission lines provided reasonably similar measurements at 30 MHz, where their frequency bands overlap.

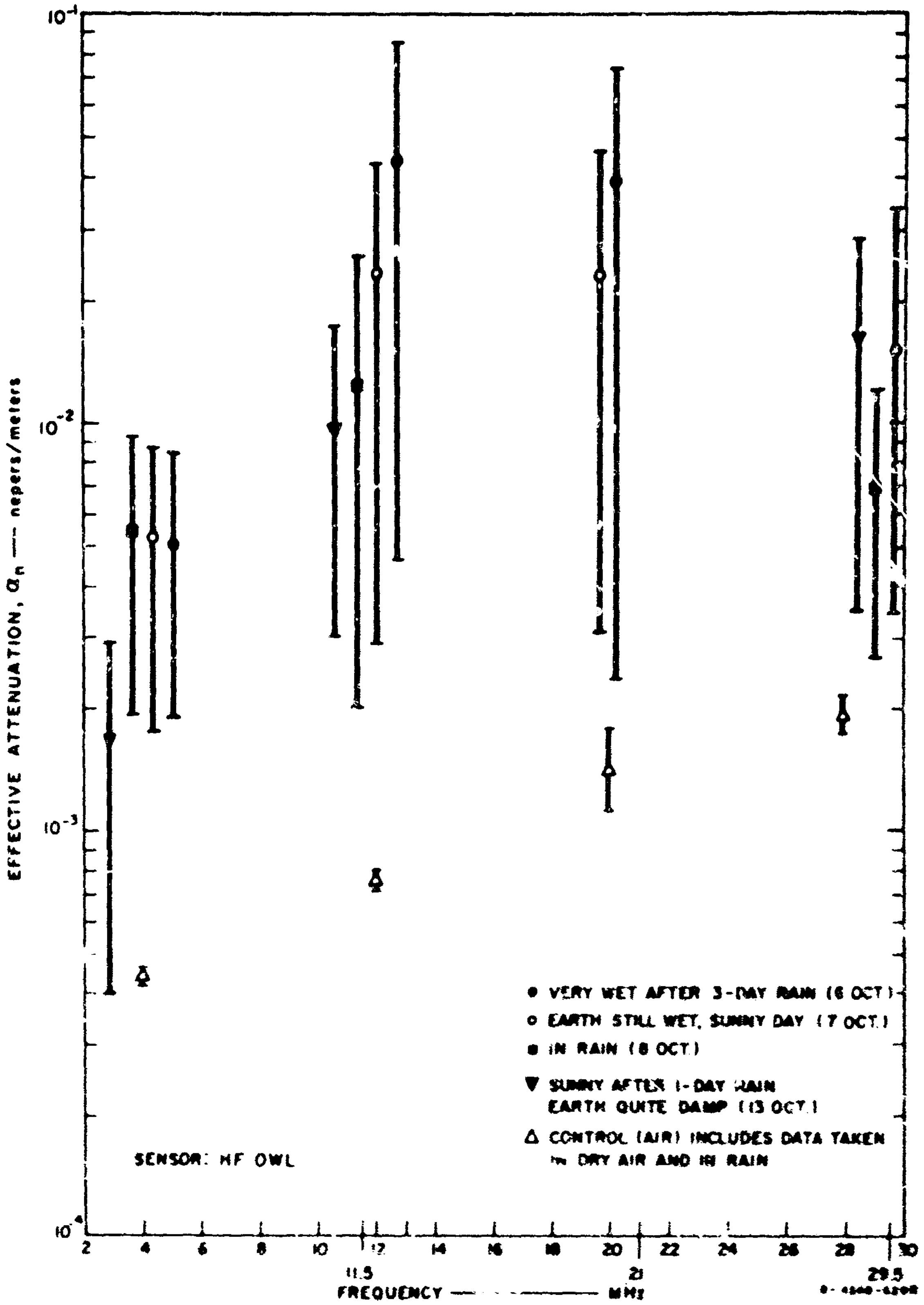

FIG. 33 HF ATTENUATION IN RED ALDER, HOH FOREST

Figure 34 is a summary plot of effective conductivity, σ_n, as a function of frequency for all foliage samples measured in the Hoh Valley. The frequency bands covered by the VHF (brass) and HF (aluminum) OWL's are indicated. From Fig. 34, one can choose an average maximum value of effective conductivity for the three dominant species found in the Hoh Forest, estimating σ_{max} as 3.0×10^{-4} mho/meter, and apply this value to theory as the upper limit of effective conductivity to be found in the area in the month of October. This application is valid because measurements were made in the most dense growth (of each species) to be found in the area. Refinement of the sampling technique to allow statistical handling of the data could provide values of true mean, upper, and lower bounds of effective conductivity to be used in describing the Hoh Forest.

The values shown for 30 MHz and above in Fig. 34 were measured with the VHF line, which was used in spruce and maple, as well as in alder. The low values obtained in Sitka spruce are from measurements made before the autumn rains began. In all other cases, the earth was quite moist at the time of measurement.

One way to summarize the lossy behavior of the dielectric medium is to plot the loss tangent (δ_n) as a function of frequency. The entire distribution of δ_n values obtained from measurements in the Hoh Forest is shown in Fig. 35, which is plotted with a power scale for convenience. Obviously, there are two definite groupings in the distribution of δ_n values. The maximum variation is approximately defined by the upper curve in Fig. 35, which might be taken as the environmental upper limit. The minimum variation, somewhat better defined, may be approximated by the lower curve. The hyperbolic form of the lower curve may be more easily seen in the Cartesian coordinate graph of Fig. 36, where only the δ_n values of the lower grouping have been plotted. These upper and lower limits, separated by nearly one order of magnitude, serve to illustrate two techniques for analyzing OWL measurements. For the higher grouping, the data were normalized to values obtained in air as described in Sec. VI-D, using the full analysis. This method tends to stress the

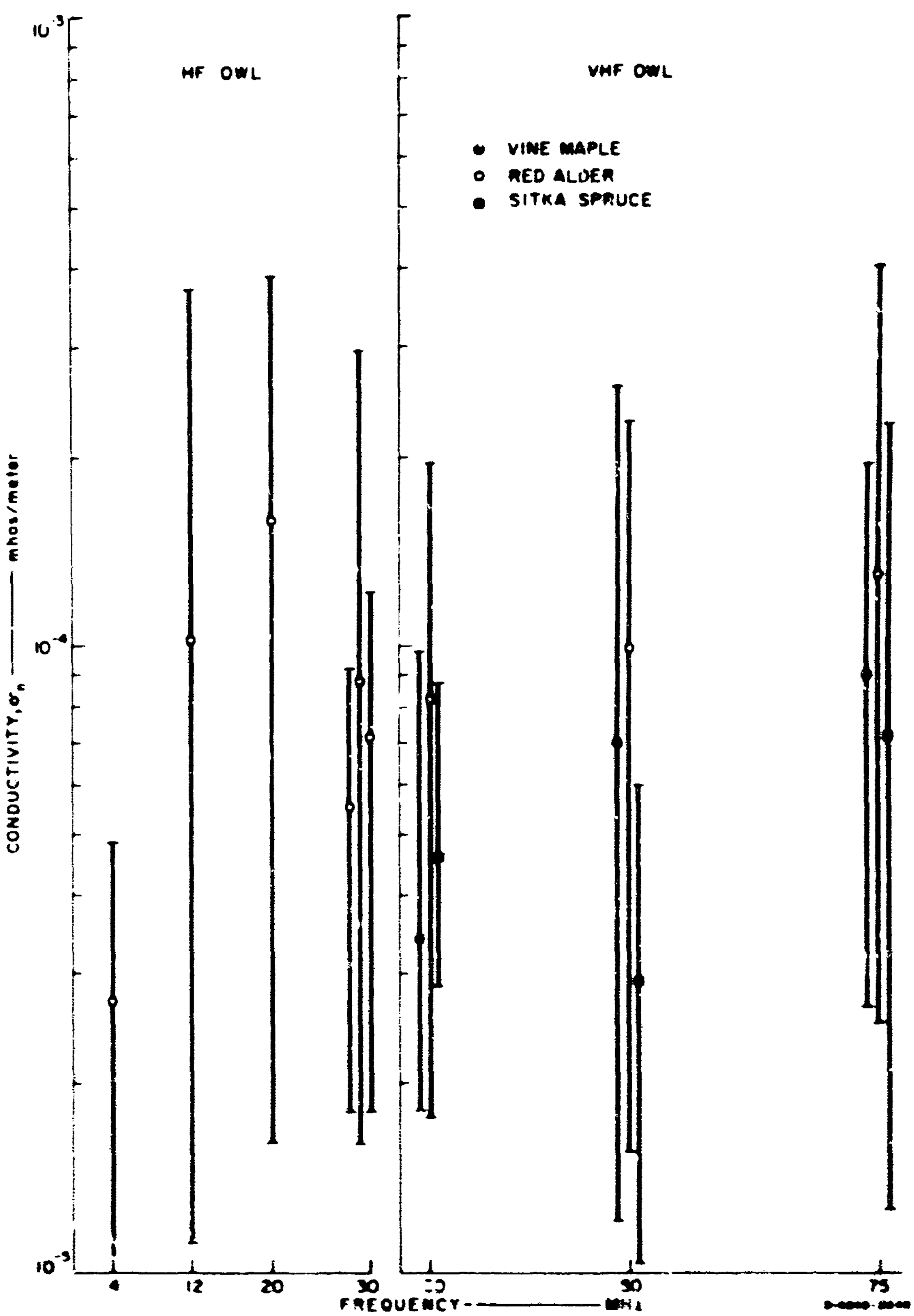

FIG. 34 EFFECTIVE CONDUCTIVITY IN THREE DOMINANT TREE SPECIES, HOH FOREST

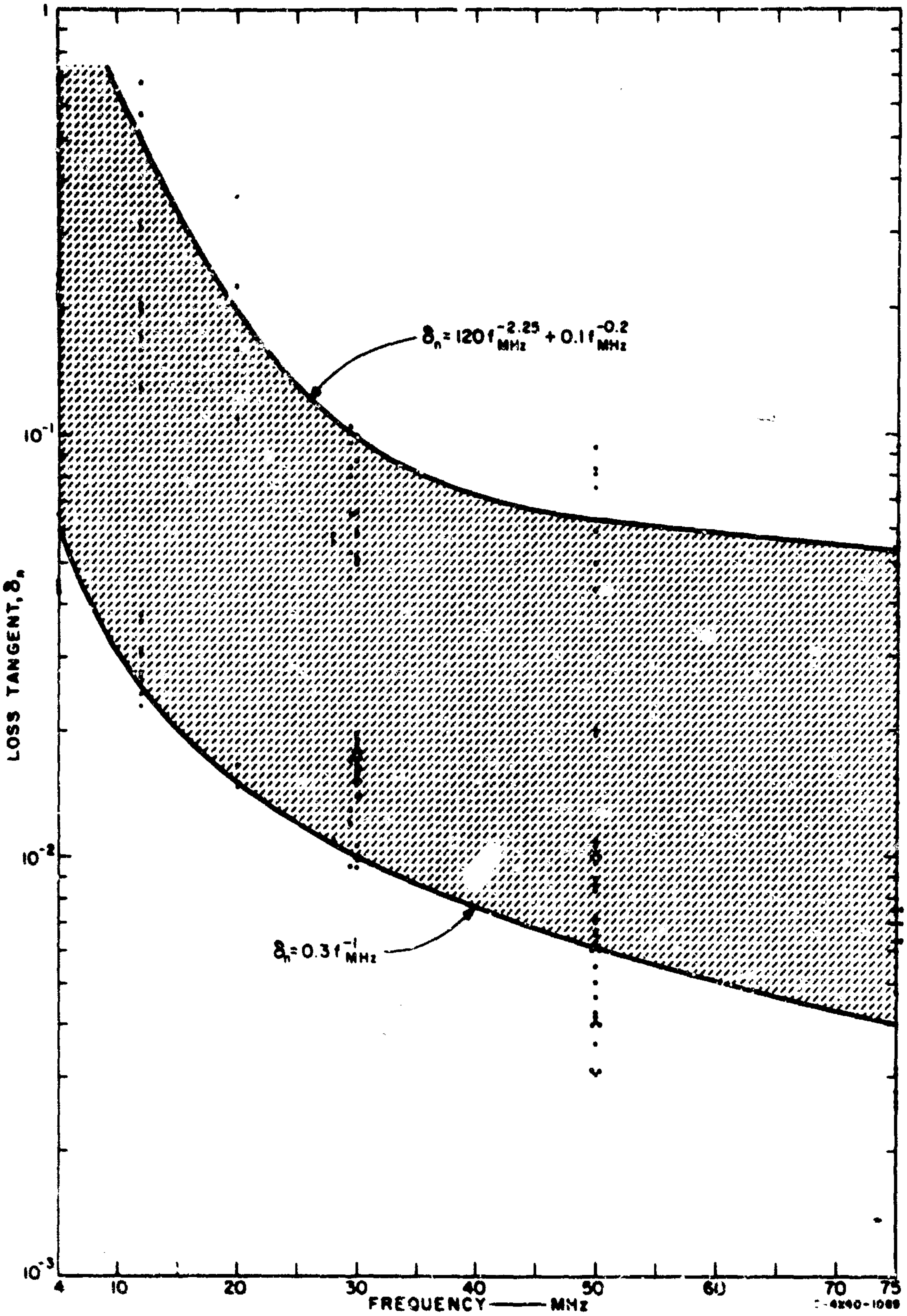

FIG. 35 EFFECTIVE LOSS TANGENT DISTRIBUTION FOR ALL SAMPLES TAKEN IN HOH VALLEY

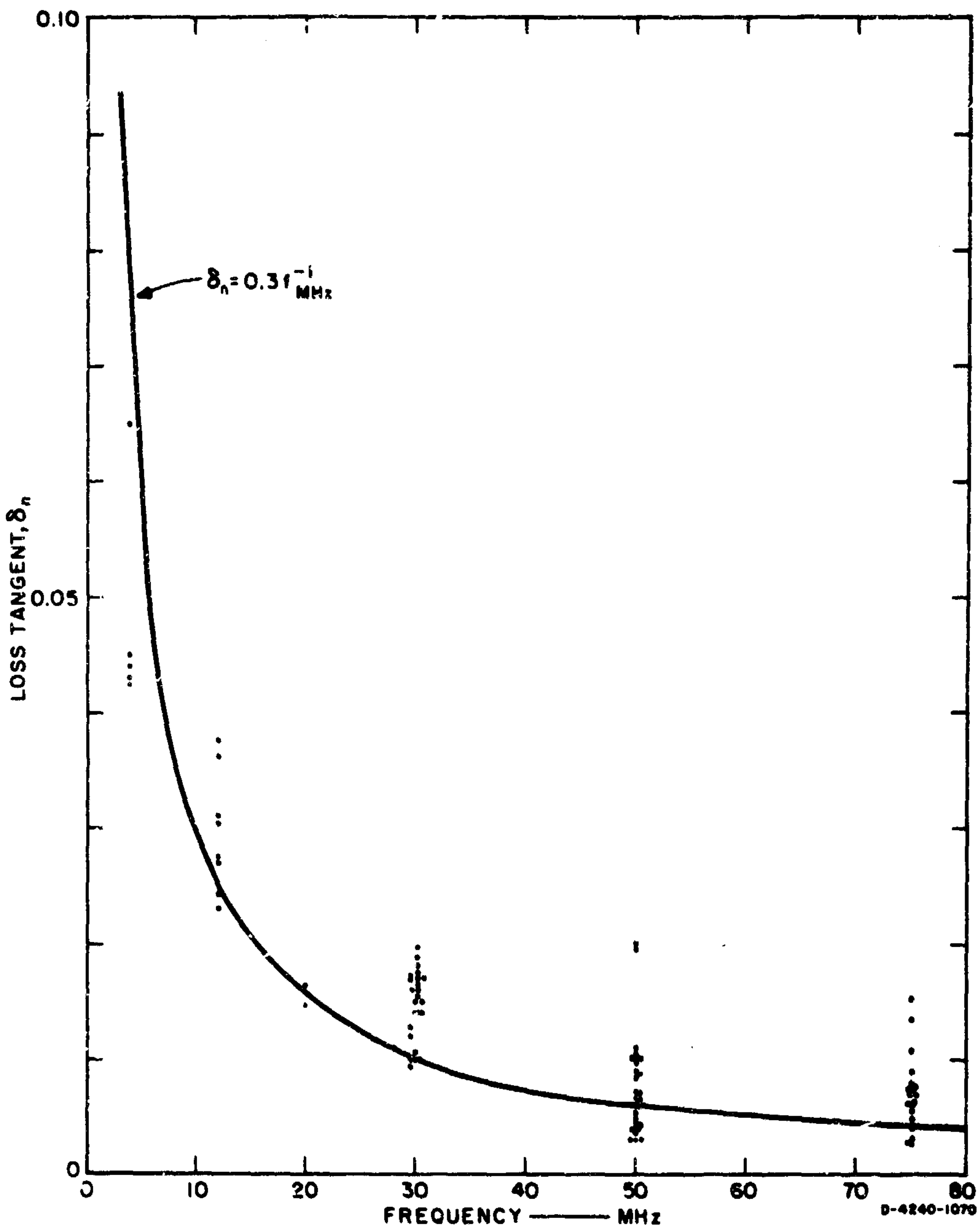

FIG. 36 LOWER GROUPING IN LOSS TANGENT DISTRIBUTION FOR THE HOH VALLEY

effect of axial inhomogeneity in the sample, which is reflected mostly in ARG Z_o for the characteristic impedance of the OWL in the sample medium. Thus the upper limit may be thought of as representing the effective contribution of scattered clumps of relatively dense foliage in a definitely inhomogeneous medium. For the lower grouping, the ARG Z_o was neglected (see Sec VI-E) in the final normalization equation for δ_n only, although it was included in the computation for the measured value of Γ. This has the effect of minimizing imbalance between open and short-ended conditions for the OWL measurements. Thus the lower limit might reasonably well represent the effective loss for a system of foliage clumps evenly distributed throughout a volume of air.

The effective permittivity, ϵ_{rn} did not vary appreciably in the several samples taken with the VHF OWL in the Hoh Forest. Representative values fell between 1.02 and 1.06, with a mean of about 1.04. We assume this low value was caused by the Fiberglas case, since the HF OWL measurements for the red alder typically ranged from 1.04 to 1.33, with a mean ϵ_{rn} of 1.2. If we increase the ϵ_{rn} values for the VHF OWL by the factor indicated in the appendix, to compensate for the presence of the Fiberglas case, the VHF mean becomes 1.2.

Several auxiliary checks of equipment performance were made, to ascertain how the OWL's were sensing their environment. While in Sitka spruce, the VHF line was rotated about its long axis without noticeable effect on its impedance. During measurements in the red alder, the line was tilted up from horizontal at one end, and also raised in its entirety to several different heights (6, 8, and 12 ft) above earth without causing more than a 10-percent change in the results. The same order of effect applies to a shift axially of about 1/16 wavelength.

The maximum radius of effect about each OWL was also checked, at the first current node from the input, by body proximity. This varied from 2 to 3 ft for the VHF OWL to 3 to 10 ft for the HF OWL.

V SOURCES OF PROBABLE ERROR

A. THEORETICAL ERROR

Several sources of probable error are inherent in the theoretical assumptions underlying the use of transmission lines in a foliage medium. The most important are:

Scattering--Scattering introduces some error (see Sec. II-E). Measured values of α may be low by a few percent at HF if the model is reasonable, but scattering experiments in forests indicate a much more complex problem, especially at VHF, whose aspects will be investigated under a separate program.

Detuning by Medium--Imbalance between the two transmission-line conductors causes some radiation, hence an error in α and β as calculated from impedance measurements. An attempt to compensate was made by careful choice of foliage of relatively uniform density. (See, however, Fig. 15 and Sec. IV-B.) An imbalance can be detected by comparing open with short impedances and by observing Z_o computed from measurements at different line lengths (Z_o should be mostly real, Z_{oc} and Z_{sc} mostly imaginary--and conjugate).

Axial Inhomogeneity of the Sample Medium--Variations in the density of the foliage medium in the direction of the OWL conductors will cause the medium to "look different" to the OWL short-ended from the situation during open-ended measurement. The result is that ARG Z_o = 1/2 (ARG Z_{oc} + ARG Z_{sc}) becomes larger than what one would measure in an homogeneous medium, perhaps enough to increase σ, δ, or α values by ten times. One will rarely find an homogeneous medium, but this effect can be minimized in normalization by partially neglecting ARG Z_o, by shifting the OWL axially or by swapping input-ends for the OWL, and averaging impedances, or by obtaining very many readings and applying statistics, as discussed in Sec. VI.

Shorting Between Conductors--This becomes a problem when the foliage surfaces are very wet. In the Hoh rain forest we solved it by insulating the VHF OWL within its Fiberglas case,* at the sacrifice of some accuracy (perhaps by a factor of 1.6). We also tried spraying the conductors with an insulating coating: Epoxy paint worked very well on the HF OWL, but since the VHF OWL has a trombone section, its terminal end was necessarily bare. We feel that flexible neoprene rubber tubing stretched about each conductor may serve to insulate the VHF OWL without impairing its tuning capability.

Termination of Transmission Lines--The short termination is excellent but the open is limited by air conductivity. Effects of foliage should be eliminated at the open end by removing foliage touching conductors.

B. EXPERIMENTAL ERROR

Probable errors arising from the experimental and analytical techniques used are estimated as:

Bridge Readings--Impedance can be read and computed to within 1.5 percent.

Linear Measurements--For the VHF line, lengths can be measured accurately to ±0.5 mm (±0.0001λ at 50 MHz). HF line lengths are known to better than ±0.001λ at 30 MHz.

Bridge Sensitivity--The bridges detect a change in length of less than 0.001 wavelength (when the VHF line is being tuned).

Computing Errors--The error in α is about ±3 percent; β error is about ±0.5 percent in the resonant technique, ±4 percent in the impedance technique.

Signal Generators--Frequency can be read to ±0.1 percent from instrument dials. (No frequency counter has yet been used.)

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* A hand-model hair dryer was used to keep the contents of the case dry.

VI RECOMMENDED SAMPLING TECHNIQUES

The recommendations in this section are based on experience gained in obtaining and analyzing the data presented in the previous sections.

A. SAMPLING FOLIAGE WITH THE VHF OWL

Two people should be able to set up and operate the VHF equipment without difficulty. The transmission line with its Fiberglas case weighs about 35 lb and if it is left in its case can be carried and placed by one person.

The most important condition to remember when placing the line in vegetation is that the medium surrounding the line should be approximately homogeneous. If large stems are equally distributed on either side of the line, serious unbalancing of the line can be avoided; but vegetation may touch the Fiberglas case without significant effects. The distribution of vegetation is not critically important, but it should appear to be about equal when the line is viewed end-on. Foliage should not be allowed to intrude between the conductors of the trombone termination, because it may impair the quality of the open circuit. Foliage may touch the shorting disc.

Each setup* can provide two sets of effective values for the dielectric characteristics of the foliage medium if the line is first tuned to resonance for one set of readings, then extended to some other length for another set. The procedure has been to find short-circuit resonance,

---

* A preliminary procedure must be followed when the Boonton (250A) RX meter is used to measure the OWL impedance. Before connection of the Boonton to the OWL through the appropriate half-wave coax balun, the Boonton signal generator must be tuned to the resonant frequency of the balun. This is done by connecting the balun to a dummy OWL input adaptor and adjusting the instrument's frequency until the meter will null when the capacitance drum is set at (or very near) zero, as

note the resonant length and impedance (resistive only), and check the number of quarter wavelengths in the resonant length (we usually used three at 50 MHz). These measurements provide enough information to calculate β and ϵ_r to a good approximation, when ARG Z_o is small†:

$$\beta = \frac{2\pi}{\lambda_m} \quad ; \quad \lambda_m = \frac{4}{3}\, x_R \quad \text{or} \quad \lambda_m = \frac{4}{5}\, x_R$$

$$\beta_o = \frac{2\pi}{\lambda_o} \quad ; \quad \lambda_o = \frac{V_p}{f_o} \approx \frac{c}{f_o}$$

$$\epsilon_r = \left(\frac{\beta}{\beta_o}\right)^2 \quad ,$$

where

x_R = resonant line length in meters
λ_m = wavelength in medium in meters
V_p = wave phase velocity
f_o = operating frequency (Hz)
c = speed of light in vacuum (3×10^8 meters/sec).

If Z_o, the characteristic impedance of the line (in the foliage medium), were known, we could also obtain α from the resonance measurements:

---

* described in the appendix to the Boonton manual.[11] The dial readings under this condition are noted as:
f_o--the operating frequency (read with a counter)
R_B--the balun resistance
C_B--the balun capacitance (kept to less than 0.15 picoFarads)
and held as initial conditions for the succeeding measurements with the OWL. If the frequency is to be changed, this procedure must be repeated with the proper balun cut to resonate at the new frequency.

† Note that none of the parameters discussed in this section are normalized to air data. They represent measured quantities related to the OWL configuration as well as to the sample medium.

$$\alpha \approx \frac{|Z_o|}{x_R Z_R}$$

$$Z_R = \frac{4R_B R_R}{R_B - R_R} \quad \text{(for the Boonton RX meter with coax balun input)} \quad ,$$

where the approximation for α is valid whenever

$$\frac{Z_o}{Z_R} \lesssim 0.15 \quad ,$$

and

Z_R = impedance of the line (resistive at short-circuit resonance)

R_B = impedance of the balun (resistive alone at open-circuit resonance)

R_R = resonant resistance of the line and balun as read from the Boonton RX meter.

To find Z_o for the calculation above, we must make an independent pair (open- and short-circuit) of impedance measurements at some new line length x_Z, chosen such that the sensing volume for the line with open-circuit termination will be equivalent to the sensing volume with shorted termination.

The sensing radii for the two cases may be readily checked when the line is in air, by human body proximity at the current node nearest the input to the line. Theoretically, x_Z should be $\lambda_m/8$ longer than the resonant length, x_R, to balance open and short effects. However, with the Boonton RX meter and coax balun, we obtained our best results when x_Z was about $\lambda_m/16$ longer than x_R. Use of instruments other than the Boonton (250A) will require checkout in air to find the best way of estimating x_Z for later application in foliage.

If two impedance measurements are made with x_Z constant, one with the line open, one with the line shorted, the readings taken with the RX meter are:

R_s, C_s } dial readings from Boonton for calculation of Z_{sc}

R_o, C_o } dial readings from Boonton for calculation of Z_{oc}

x_Z - line length.

Then Z_o may be found:

$$Z_o = (Z_{oc} Z_{sc})^{1/2} \quad ,$$

where both Z_{oc} and Z_{sc} may be calculated for the Boonton (250A) readings from the general expression

$$Z = T \frac{\left(\frac{1}{R} - \frac{1}{R_B}\right) - j\omega\,(C - C_B)}{\left(\frac{1}{R} - \frac{1}{R_B}\right)^2 + \omega^2 (C - C_B)^2} \quad .$$

Here,

R = either R_o or R_s

C = either $\pm C_o$ or $\pm C_s$,

depending on whether Z_{oc} or Z_{sc} is to be calculated, and

T = balun transformation ratio, approximately $4\angle 0°$ for the coax balun, R_B and C_B are the initial conditions for the balun, and

$\omega = 2\pi f_o$*.

From Z_o and Z_{sc}, α and β, the components of the measured propagation constant Γ (not normalized) can be calculated, since

$$-j\Gamma = (\beta - j\alpha) = \frac{1}{2x_Z} \ln \frac{1 - Z_{sc}/Z_o}{1 + Z_{sc}/Z_o}$$

---

* If resistances are in kilohms and capacitances in picoFarads, then $\omega = 2\pi f_o \times 10^{-9}$, with f_o in Hz.

or

$$\alpha = \frac{-1}{4x_Z} \ln \frac{(1 - a)^2 + b^2}{(1 + a)^2 + b^2} \text{ nepers/meter}$$

$$\beta = \frac{1}{2x_Z} \left[k\pi - \tan^{-1}\left(\frac{1 - a}{b}\right) - \tan^{-1}\left(\frac{1 + a}{b}\right) \right] \text{ radian/meter} ,$$

and

x_Z = line length at which Z_{sc}, Z_{oc} were measured

a = real component of Z_{sc}/Z_o

b = imaginary component of Z_{sc}/Z_o

k = 2N - 1

N = number of half-wavelengths ($\lambda_m/2$) in which x_Z is contained.

Since the volumes sensed by the OWL are approximately sinusoids of revolution, the data from the two measurements (resonance and open-short) discussed above do not represent any convenient volume of the foliage medium about the line. A schematic of the situation is shown in Fig. 37, where, for simplicity, only half cross sections of the active regions are used. Obviously, if one wanted to sample a cylindrical volume of foliage, he could approximate the condition fairly well at any single frequency by shifting the OWL along its long axis by $\lambda_m/4$ and repeating the two measurements as in the first setup, then using their mean. If more precision is desired, four setups might be made, with axial shifts of $\lambda_m/8$ between each, at one frequency.

B. SAMPLING FOLIAGE WITH THE HF OWL

Here, technique is quite important; and the previous remarks concerning placement of the VHF OWL for good foliage distribution apply almost as critically to the aluminum OWL. Tuning by extension of the HF line is not practical. Instead, operating frequencies should be chosen such that $(2n - 1)\ \lambda_m/8$ wavelengths ($n = 1, 2, 3, \ldots$) occur along the existing length of the line. The required frequencies can be readily calculated for the several available OWL lengths for the case

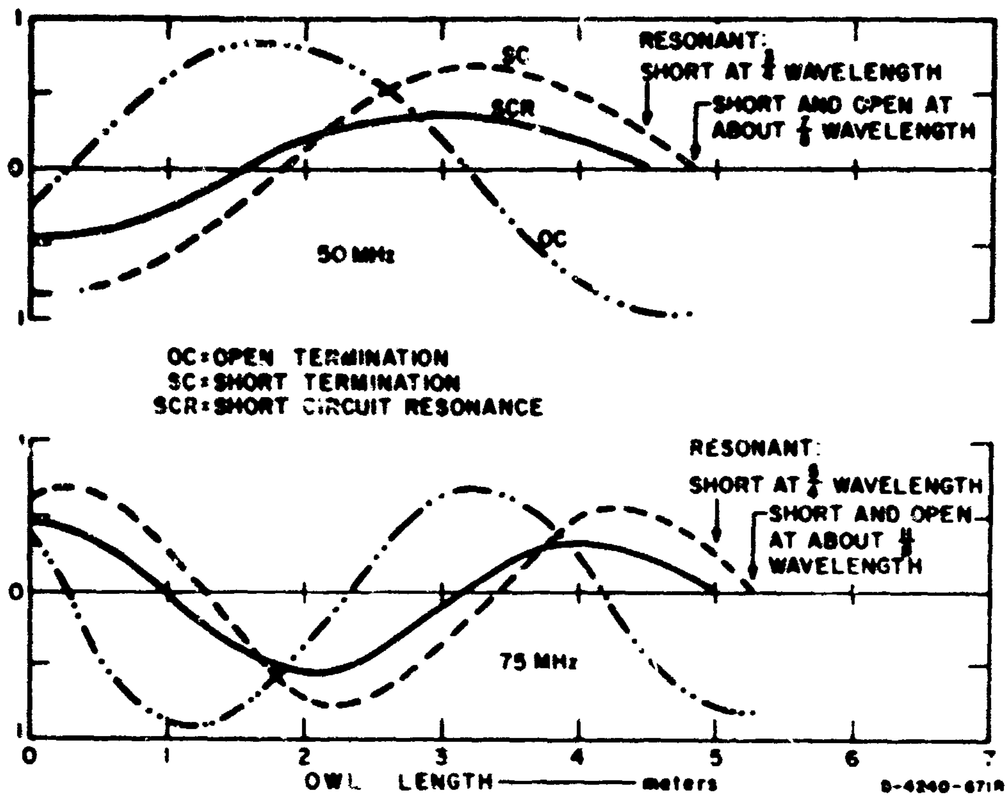

FIG. 37 HALF-ENVELOPES OF OWL SENSING REGIONS

of an air dielectric. Values for operation in air, given in Table II, may be assumed to apply well in foliage.

The radius of effect of the HF line at frequencies below 10 MHz may be less in foliage than in air because of shielding effects of the vegetation. The maximum possible sensing radius of the HF line in air is about 20 ft,* but with careful attention to frequency-tuning technique, the effective sensing radius should average between 4 and 6 ft. The HF OWL should usually be set up parallel to the earth.

* This value applies to either open- or short-circuited termination, but not to both. If the line is highly sensitive when open-circuited, it will be very insensitive when shorted at the same frequency (and length), and vice versa.

Table II

OPTIMUM FREQUENCIES FOR THE HF TRANSMISSION LINE

No. of Line Sections	x_Z (ft)	x_Z (meters)	n^*	λ_o (meters)	f_o (MHz)	$k^\dagger$
1	22	6.7	1	17.86667	16.791	1
2	42	12.8	1	34.1333	8.789	1
			3	9.3091	32.227	5
3	62	18.9	1	50.40	5.952	1
			3	13.7455	21.825	5
			5	7.9579	37.698	9
4	82	25.0	1	66.667	4.5	1
			3	18.182	16.5	5
			5	10.526	28.5	9
5	102	31.05	1	82.800	3.623	1
			3	22.58182	13.285	5
			5	13.0737	22.947	9
			7	9.200	32.61	13

* The number of quarter-wavelengths contained in x_Z. The recursion formula is

$$\lambda_o = \frac{8x_Z}{4n - 1} , \quad n \text{ odd} .$$

† Twice the number of half-wavelengths in which x_Z is contained, less one (used in the equation for computation of δ).

Two men can handle the setup job, but for maximum safety and efficiency it is preferable to have four to six. They will take about one day to set up the entire line (120 ft long) in foliage of medium density (visibility fairly good; about 3 ft between stems).

The sampling volume of the HF line can be varied from 22 to 122 ft in length. If the length is to be varied, it will be easier to begin with the 22-ft length and progress by adding pipe sections. Removal of pipe sections is likely to proceed with difficulty and random sequence. As with the other line, it is important that the HF OWL open termination be free of foliage between conductors, to a reasonable extent, especially in wet weather. This technique of varying OWL length should provide the best estimates of foliage parameters, if the results for the various lengths are averaged for each frequency.

If enough frequency diversity can be introduced in the HF OWL measurements at each "station"* (including all possible lengths of the HF line), the mean of the results at each frequency will provide effective dielectric constant (complex) values for a cylindrical volume at least 7 ft in diameter about the long axis of the line. (Probably six frequencies, such as 3.62, 4.5, 5.95, 8.79, 13.28, and 16.5 MHz from Table II, would suffice, but it is well to include some frequencies near 30 MHz, also.) This is a rather rough technique: it will not provide the best definition of the variation of loss in the sample as a function of frequency.

To obtain good statistics for a grove or other volume of vegetation, lateral movement (horizontal and probably vertical) of the HF line in 10 foot increments will be necessary. (We do not recommend moving the HF line axially without shifting its supports.) This will require knock-down and re-assembly of the line involving perhaps three weeks' time to measure a grove 100 by 40 ft, with three days of work per measurement station. (This is not enough time for jungle operations, but may be adequate in Temperate Zone forests.)

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* For OWL measurements we define a station as the position or positions (of either OWL) required to sample one cylindrical volume (of the medium surrounding the line) having a length equal to the greatest OWL length used in obtaining the samples at that position.

Although vertical movement at one setup position is possible with extension poles, it would require removal of the pipe (conductors) except for vegetation having a predominantly vertical pattern (for example, bamboo). Alternatively, a set of rope slings might be employed, especially in the less dense foliage.

The primary results from HF OWL measurements will be in the form

$$Z_{oc} \quad , \quad Z_{sc} = R \pm jX \quad ,^{*}$$

where

R = measured resistance

X = measured reactance,

if a series-substitution impedance bridge such as the General Radio 1606-A is used. This bridge has an unbalanced input, which requires a balun connection to the OWL.† Half-wave resonant coax baluns will not be efficient enough for the HF line. We used toroid baluns wound for the frequency range. The balanced terminals of these baluns had about 2-inch spacing, and the spacing was spread out to 40 inches at the OWL by 80-inch extension rods. The bridge was zero-balanced through the balun, etc., by connecting a shorting rod or plate across the 40-inch end of the spreader extensions. This method affects the transformation ratio of the balun and coax (and is quite dependent on length of coax between bridge and balun). But since only impedance ratios are used in calculating α and β, the uncertainty cancels in the equations.

---

* Generally, $Z = T[R + j(X - X_0)/f_0(\mathrm{MHz})]$ where X_0 is the zero-balance bridge reactance setting. But see General Radio instruction manuals for specific equipment.[13]

† A balanced input bridge, such as the Wayne Kerr, Ltd. Model B-801, would be ideal in this application if the detector could be sufficiently well shielded from the OWL.

The impedances calculated* from the R ± jX readings for the HF line are then used in the equations relating Z_{oc} and Z_{sc} to Z_o and Γ as discussed for the VHF line.

C. CALIBRATION OF OWL IN AIR

The radius of effect for both OWLs should be checked (preferably by proximity to earth) periodically, especially whenever new measuring instruments (including null detectors) are employed. At the same time, one should ascertain the optimum VHF line length to use for x_Z, by determining the length that causes near-equal radii of effect for open and shorted terminations.

If possible, calibration for control data in the air should always be done before and after measurements in foliage, under the same atmospheric conditions and with the same OWL lengths.

D. NORMALIZING SAMPLE DATA TO AIR VALUES

Following a development similar to that of Kirkscether,[1] we have attempted to balance out the errors inherent in the OWL impedance measurement technique by using a comparison to a standard of calibration: air. If OWL length is held constant during both sample and control measurements, and frequency is approximately invariant, the parameters of the sample medium can theoretically be computed without regard to inherent OWL losses, minor input circuit imbalance, etc. Using primed symbols to represent results of control measurement in air, the subscript n for normalized parameters, and beginning with the expression for the propagation constant from Sec. II:

---

* To transform impedance through any length ℓ of lossy transmission line, when the open and short impedances have been measured at ℓ, and the unknown, Z, connected at ℓ, results in a measured Z_m:

$$Z = \frac{Z_{oc}(Z_m - Z_{sc})}{Z_{oc} - Z_m}$$

$$\Gamma = \frac{1}{x_z} \operatorname{arctanh} \left[\frac{Z_o}{Z_{oc}} \quad \text{or} \quad \frac{Z_{sc}}{Z_o} \right] ,$$

where Γ is the non-normalized propagation constant, as measured, we can now write normalized foliage constants:

$$\epsilon_{rn} = \frac{\omega'}{\omega} \frac{Z_o'}{\beta'} \operatorname{Im} \left\{ \frac{\Gamma}{Z_o} \right\} ,$$

$$\delta_n = \cot \operatorname{ARG} \left\{ \frac{\Gamma}{Z_o} \right\} ,$$

and the other parameters follow from these:

$$\sigma_n = \omega\epsilon_o \epsilon_{rn} \delta_n$$

$$\alpha_n = \frac{\omega\delta_u \epsilon_{rn}^{1/2}}{2c}$$

$$\beta_n = 2 \frac{\alpha_n}{\delta_n}$$

$$\Gamma_n = \alpha_n + j\beta_n .$$

This last equation gives the normalized propagation constant. Note that the components of Γ (α and β) in Secs. II, VI-A, and VI-B, are not normalized in that context; indeed, it is the β of Sec. II (etc.) that, when computed for an air measurement, must be assigned the role of β' for normalization.

One further point: The characteristic impedance of the OWL in the sample, Z_o, appears twice in succession during the normalization. And ARG Z_o controls first the magnitude of the real part of Γ (hence of ARG Γ) then, later both ARG Γ and ARG Z_o control the magnitude of the loss tangent:

$$\delta_n = \cot [\operatorname{ARG} \Gamma - \operatorname{ARG} Z_o]$$

$$= \cot [\operatorname{fcn} (\operatorname{ARG} Z_o, \operatorname{MOD} Z_o, Z_{oc}) - \operatorname{fcn} (\operatorname{ARG} Z_o)] .$$

E. ANALYZING THE EFFECT OF AN INHOMOGENEOUS MEDIUM

Even when the VHF OWL is left in its Fiberglas case, it will be sensitive to the medium in the vicinity of the case, and if this medium is not really homogeneous, the OWL will behave as if more than the actual losses were incurred in the medium. This arises from the axial inhomogeneity of the medium, and will be more pronounced when the Fiberglas case is removed. Since the characteristic impedance (Z_o) of an OWL in any dielectric medium contains a compact representation of the medium itself, and is relatively easy to compute, we recommend Z_o as the primary check on behavior of an OWL in relation to the medium. Mathematically, the impedance per unit length and admittance per unit length are functions of the electrical characteristics of the medium and of the transmission line itself:

$$z = r + j\omega L \quad , \quad y = g + j\omega C$$

where r, the resistance per unit length of the OWL, depends primarily on the conductivity of the OWL conductors. Also, in a non-magnetic medium, L, the inductance per unit length of the OWL, depends primarily on the inductance of the OWL conductors. However, the conductance per unit length, g, depends almost entirely on the conductivity of the medium about the conductors and the capacitance per unit length, C, depends on the dielectric constant of the medium. Thus Z_o represents the medium as well as the OWL:

$$Z_o = \sqrt{\frac{z}{y}} = \sqrt{\frac{r + j\omega L}{g + j\omega C}}$$

In air, a medium whose conductivity $\sigma \to 0$ and whose permittivity $\epsilon_r \to 1$, we expect to find that Z_o is almost entirely real, and relatively large, because with low-loss conductors $r \to 0$; with low leakage through the medium $g \to 0$; with low ϵ_r, C is small; and

$$Z_o' \approx \sqrt{\frac{L'}{C'}} \quad .$$

which is the familiar low-loss formula of transmission line theory. If we now consider a non-lossy medium other than air, having a larger value of ϵ_r (for example 4), we find the characteristic impedance reduced to

$$Z_o \approx \sqrt{\frac{L'}{\epsilon_r C'}} \approx \sqrt{\frac{L'}{4C'}} \approx \frac{1}{2} Z_o'$$

where primes indicate values we had in air. Extending this approach further, to a lossy dielectric medium ($\sigma < \omega\epsilon$) we can approximate

$$Z_o \approx \sqrt{\frac{j\omega L'}{g + j\omega\epsilon_r C'}} \approx \sqrt{\frac{\omega^2\epsilon_r L'C' + j\omega L' g}{g^2 + (\omega\epsilon_r C')^2}} \quad .$$

Thus in a lossy medium, Z_o should have an argument given approximately by

$$Z_o \approx \frac{1}{2} \text{Arctan} \frac{g}{\omega\epsilon_r C'}$$

but since[1]

$$g = \frac{\sigma C'}{\epsilon_o}$$

where σ is the conductivity of the lossy dielectric medium,

$$Z_o \approx \frac{1}{2} \text{Arctan} \frac{\sigma}{\omega\epsilon_r \epsilon_o}$$

and if the loss tangent of the medium is

$$\delta = \frac{\sigma}{\omega\epsilon} \quad ,$$

we have

$$\text{ARG } Z_o \approx \frac{1}{2} \text{ Arctan } \delta \quad ,$$

or

$$\delta \approx \tan 2 \text{ ARG } Z_o \quad .$$

We expect, therefore, to find a complex characteristic impedance for any lossy dielectric medium, whose argument (or phase angle) is positive. Moreover, the magnitude of Z_o for an OWL in such a medium must be smaller than it was in air. The ratio

$$\frac{Z_o'}{Z_o}$$

provides most of the information about the dielectric constant of the medium (relative to that for air); the ARG Z_o indicates the lossiness of the medium.

We measure Z_o by reading the OWL input impedance with its far end first shorted by a large aluminum disc, then left open. From these readings,

$$Z_o = \sqrt{Z_{oc} Z_{sc}}$$

is used to generate Z_o, in both air and foliage media. This technique suffers in its accuracy from the poor axial symmetry found in almost any foliage medium. Since the medium is essentially a dielectric, only the electric field (E field) about the OWL conductors is affected by the foliage (to any measurable extent). But the E field collapses to nearly zero in the vicinity of a voltage node on a transmission line (refer to Fig. 37). Thus there is no E field near points along the OWL at the shorted end and at $n(\lambda/2)$ distant from the short. When the end is open, this pattern of nodes (and E fields) is shifted axially by $\lambda/4$. The effect is one of having two entirely different media represented in Z_o:

one by Z_{oc}, the other by Z_{sc}. If inhomogeneity is appreciable, the ARG Z_o can become quite large, even though σ in the foliage is actually small, producing spurious values of effective conductivity, attenuation, etc., for the foliage.

The representation of dielectric constant will also be in error, but to a lesser extent, since for foliage, ϵ_r is bound to be between 1.0 and 2.0, and is generated from a ratio of large numbers, since $|\Gamma| \approx \beta'$ and ARG $\Gamma \rightarrow 90^0$:

$$\epsilon_{rn} = \frac{\omega'}{\omega} \frac{Z_o'}{|Z_o|} \frac{|\Gamma| \sin(\text{ARG } \Gamma - \text{ARG } Z_o)}{\beta'} .$$

The best way to overcome this difficulty is to make enough measurements so that such errors take on a random nature and can be reduced through statistical analysis. A simpler (though crude) approach would be to shift the OWL axially by $\lambda/4$ between measurements and use mean impedance values in computations. Whenever these have not been the sampling techniques used, one may attempt to minimize the effect of axial inhomogeneity during the normalization procedure, as we did for all OWL data in this report taken after August 1965, simply by neglecting ARG Z_o in the equation for computing the normalized loss tangent. ARG Z_o still controls the real part of Γ, and the double dependency of δ_n on ARG Z_o is thus reduced one order:

$$\delta_n = \cot [\text{ARG } \Gamma]$$

$$= \cot [\text{fcn} (\text{ARG } Z_o \quad , \quad \text{MOD } Z_o \quad , \quad Z_{oc})] \quad .$$

The removal of -ARG Z_o from the expression for δ_n must always result in a decrease of apparent loss, for ARG Γ must be positive in the physical realm, while ARG Z_o must be positive (or very near zero) for any successful measurement. Thus the neglect of ARG Z_o once in the analysis amounts to a minimization of the effect of axial inhomogeneity on foliage loss measurements. It does not affect the value of ϵ_{rn} significantly.

F. STATISTICAL HANDLING OF RESULTS

A measurement station has been defined (for our purposes) as a position or set of positions of the transmission line required to generate enough data to describe (via mean results) a cylindrical volume of the medium surrounding the line. The statistical approach may be readily extended to encompass any volume of foliage if a regular sampling procedure is followed by the field crews.

Consider a grove of trees, and imagine an array of measurement stations within the grove, as shown in Fig. 38. If we require the station array to be regular--rectangular, with a constant interval between stations in both the horizontal and the vertical directions--we can assign station labels as shown and convert the array to a "sampling matrix" for data processing. Thus, the center station of the matrix would be designated C-3 in the example, and if the (constant, or nearly so) interval* between stations were known, the grove could be described

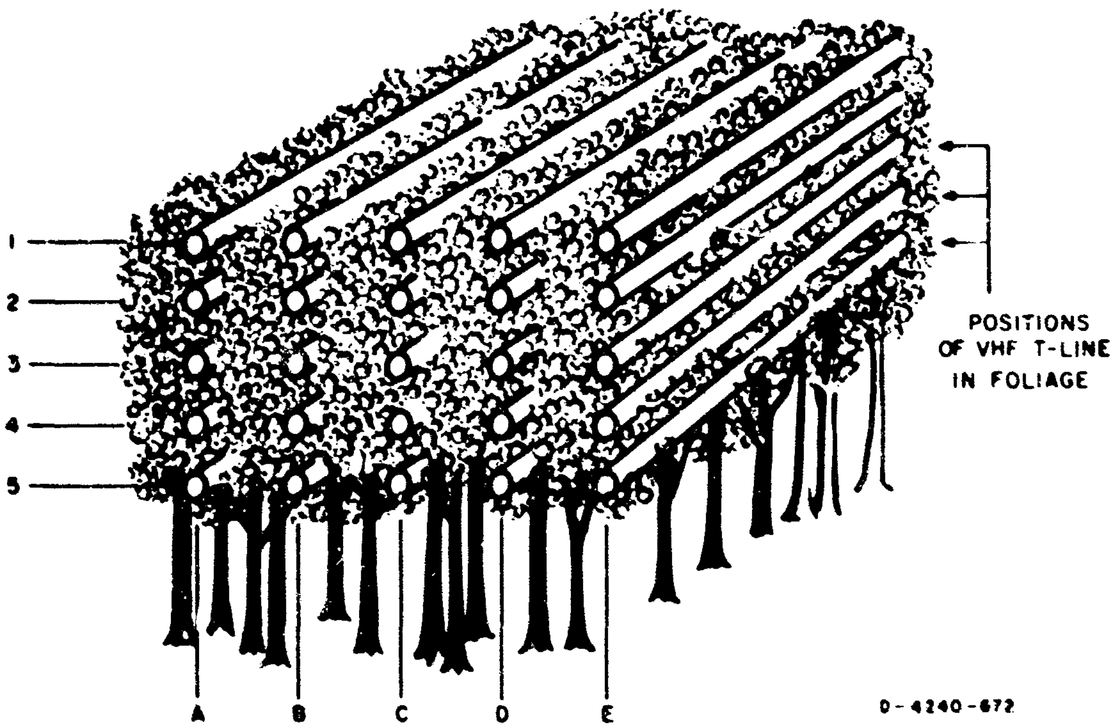

FIG. 38 SAMPLING MATRIX

* About 2 ft for the VHF line, 10 ft for the HF line.

statistically from various averages of the mean results obtained at each station. It would thus be possible to form averages to describe the grove in any desired manner, vertically, horizontally, for sub-matrices, for the foliage perimeter, etc.; and distributional variance in the sample could be studied.

For the first such sampling matrices, it will not be known how many (or how few) stations are required to describe the properties of the foliage well enough for the various uses of the data. Hence, an overly dense set of stations should be used until the results can be analyzed statistically. Therefore, the station interval should probably be halved, and once a sampling matrix has been completely measured in some volume of foliage, the matrix should be rotated 90° in the horizontal plane and another measurement set should be performed at all stations of the matrix. A series of measurements with the OWL in the vertical plane would also be valuable. Then, after all possible correlations have been studied, an operational procedure can be established for further field work.

VII USES OF DATA

Forest dielectric-constant measurements provide a quick and repeatable method for comparing the electrical properties of forests. Prospecting for radio-experiment field sites might be done by using the VHF transmission line, a battery-powered transmitter (30 to 75 MHz), a General Radio Model 1601 VHF bridge, and a battery-powered receiver. Two men could pack the instruments. A helicopter could also be used.

Data gathered systematically at checkpoints through a forest would give an indication of the usefulness of a lossy dielectric slab model (usually assumed to be homogeneous) in propagation theory. These data might also be a guide to the choice of the effective electrical properties to be included in theoretical work, especially the calculation of average effect on antenna radiation patterns and impedances.

The measurements already performed provide a near-zero-distance path loss intercept missing in the data* of Herbstreit[13], Jansky and Bailey[14], and the New Zealand Department of Scientific and Industrial Research[15]. The SRI measurements compare well with the aforementioned results, as in Fig. 39, and they provide the dielectric constant as well. If it is possible to model the decay of an effective α as a function of distance (Fig. 39)†, the OWL measurements could be used to obtain an estimate of the scale (zero-range intercept), permitting inference of radio propagation characteristics at a distance in a forest of known average electrical properties and height.

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* Where path-loss data were given by these researchers, the slopes of loss-vs.-distance curves were taken to represent attenuation, α.

† Such a model is available from recent work by Sachs and Wyatt[16], but a more straightforward approach seems desirable.

Finally, the techniques discussed offer the possibility, by mathematical conversion from σ_n and/or ϵ_{rn} to fractional water volume (see Sec. II) or biodensity (Appendix), of providing forest moisture-content readings of a quantitative nature, whereby fire danger alerts might be standardized and related to the actual foliage conditions, rather than to air humidity.

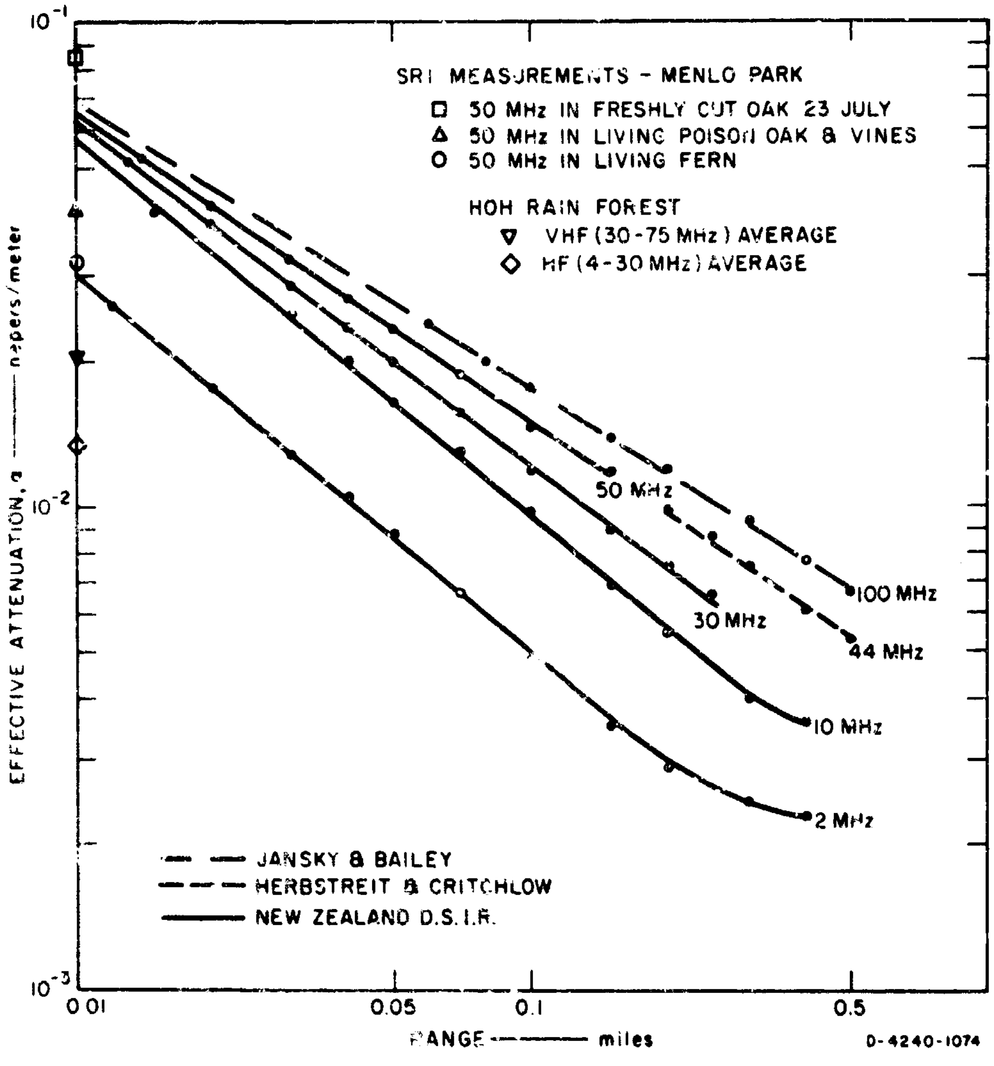

FIG. 39 COMPARISON OF PATH-LOSS ATTENUATION RATES AS A FUNCTION OF RANGE WITH ZERO-RANGE ATTENUATION RATES FROM OWL MEASUREMENTS

Appendix

EXPERIMENTS TO RELATE BIODENSITY TO VHF OWL MEASUREMENTS

Appendix

EXPERIMENTS TO RELATE BIODENSITY TO VHF OWL MEASUREMENTS

1. INTRODUCTION

The SRI VHF OWL was used to measure the attenuation α and phase constant β of quasi-transverse electromagnetic (TEM) waves traveling along its length through a pile of freshly cut willow boughs. The willows, obtained at Searsville Lake, near Menlo Park, California--between 1000 and 1600 PDT, 20 October 1965--were crisscrossed in a pile contained in a wooden bin, which in turn rested on a scale (see Fig. A-1). The changing weight of the drying willow sample was observed, and the effective complex dielectric constant within the sample was measured by use of the VHF OWL (enclosed in its Fiberglas case). The goal of the experiment was to determine whether a correlation existed between the OWL measurements and the weight of the willows (indicating the fractional volume of water remaining in the sample). The two sets of data may presumably be related by the theory of dielectric mixtures, as will be discussed.

The effective permittivity, attenuation, and conductivity of the sample were calculated from impedance measurements as described in Sec. VI and normalized to air data.

2. FRACTIONAL VOLUME OF WATER

The initial weight of the entire apparatus (see Fig. A-2) was 1312 lb at 1800 on 20 October, within six hours of the foliage cutting. After the weight stopped changing (about 23 October), the apparatus weighed 1058.5 lb. The (constant) weight of the wooden bin and OWL was 374 lb. The values given correspond to a weight loss of about 300 lb of water (assuming that some was lost before the experiment),

FIG. A-1 BIODENSITY EXPERIMENT, SHOWING IMPEDANCE METER, WILLOW FOLIAGE, BIN, AND SCALES

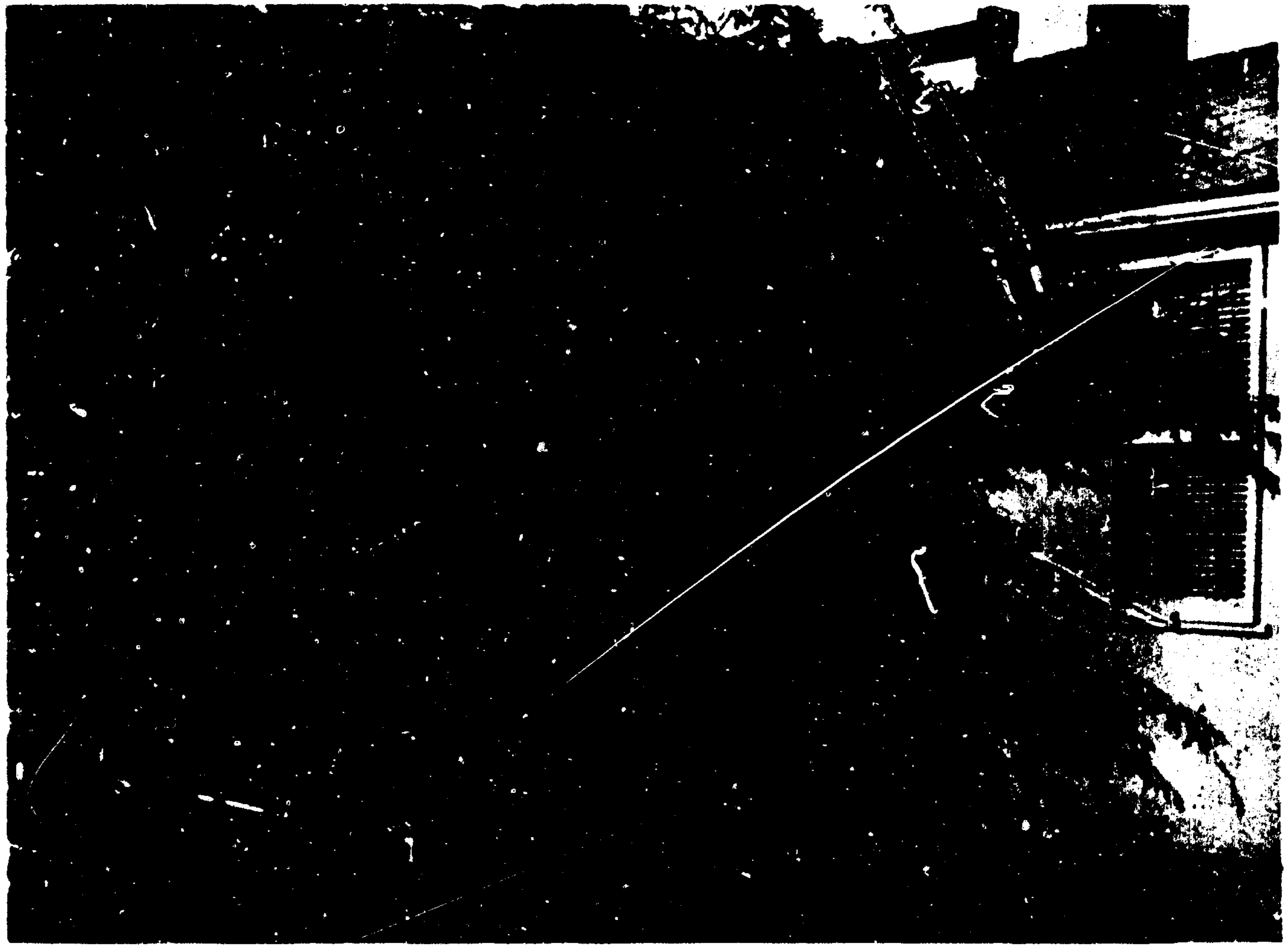

FIG. A-2 WILLOW SAMPLE AND VHF LINE TERMINATION

or a diminishment of about 30 percent by weight. Such a small change with drying may be indicative of the seasonal state of the willow. If we assume the entire weight change to have occurred from loss of water, we may calculate the fraction of the sample volume that was water at any time for which the weight is known. The total volume of the sample was calculated as 532 ft^3, but, to be conservative, we use 500 ft^3, which corresponds with a cylindrical volume of 4-ft radius and 20-ft length, representing the active sensing region of the transmission line. Only the weight at the time of interest and the final "dry" weight of the sample are needed to obtain the fractional volume of water F_w, if the total volume of the sample is known.

As an example, we calculate F_w for the first weight obtained, 1800 local time, 20 October 1965.

Dry sample weight = 684.5 lb

Weight at 1800, 20 October = 937 lb.

Thus, the weight of the water contained at 1800, 20 October was 252.5 lb; its volume was

$$252.5 \times 1.6 \times 10^{-2} = 4.03 \text{ ft}^3,$$

Then F_w at that time was

$$F_w = \frac{4.03}{500} = 8.08 \times 10^{-3}$$

for the fractional volume of water contained.

3. RELATING OWL MEASUREMENTS TO BIODENSITY

In order to correlate transmission-line measurements with weight (or biodensity) measurements made upon the sample of cut willow boughs, we wish to assess the effective permittivity of the sample independently. This can be done by applying the theory of dielectric mixtures if the constituents of the mixture (willow sample) can be described well enough.

The parameters needed are the intrinsic permittivity (ϵ/ϵ_o) of each constituent and the fractional volume occupied by each in the mixture. Neglecting leaves, which were crisply dry even before cutting and made up a very small portion of the total material (especially by weight), we had a mixture of unbound (or free to evaporate at normal temperature and pressure) water, air, and wood cellulose containing perhaps 10 or 20 percent water as bound water (which would evaporate only if the wood were oven-dried).

The fractional volume of unbound water was found by weighing at intervals until the sample weight ceased to change; the permittivity of this water was taken as 80 (it probably contains soluble salts, but less of them than sea water, which has permittivity of 81). These parameters are F_w and ϵ_w, respectively.

The parameters for the wood cellulose (and its bound water) were obtained by cutting small stem samples and testing them for permittivity (as was done by Pounds and LaGrone[5]) and for specific gravity. Then the fractional volume of cellulose was found by comparing the "dry" density of the entire willow sample with that of the average of the stem samples. The cellulose fraction was 4.6×10^{-2}, called F_c. The permittivity measurements yielded ϵ_c, which lay between 4.7 and 6.5. We thus have the parameters required for all significant constituents of the mixture, since, for air:

$$\epsilon_A = 1.0$$

$$F_A = 1 - F_w - F_c.$$

We had hoped to compare our ϵ_c values for willow with independent determinations, but a cursory search of the literature has revealed no data on the permittivity (or relative dielectric constant) of willow or any other hardwood measured under conditions other than perfectly dry (except buckeye, oak, and Wych elm; buckeye when 10- to 20-percent moist has $\epsilon_c \approx 4$ according to Skaar[17]). Hearmon and Burcham[18] tested oak and Wych elm throughout the radio-frequency spectrum, which is what is needed, but they worked with very wet (70- to 75-percent moisture content) wood.

Reference Data for Radio Engineers[19] gives ϵ_r for hardwoods in the frequency range 10 to 100 MHz of the order 1.8 to 2.7, these being dry-wood values.

Having found ϵ_c, which we will take as 4.7, and F_c for the willow stem cellulose (including bound water), we can now limit ϵ for the entire mixture of unbound water, wood, and air. The lower limit on ϵ, which corresponds to dielectric slabs in series throughout the sample volume is given by:*

$$\underline{\epsilon}_r = \left(\sum_{i=1}^{n} \frac{F_i}{\epsilon_i}\right)^{-1}$$

or

$$\underline{\epsilon}_r = \left[\frac{F_w}{\epsilon_w} + \frac{F_c}{\epsilon_c} + 1 - F_w - F_c\right]^{-1} .$$

Simplifying,

$$\underline{e}_r = \left[F_w\left(\frac{1}{\epsilon_w} - 1\right) + F_c\left(\frac{1}{\epsilon_c} - 1\right) + 1\right]^{-1} ,$$

and, employing

$\epsilon_w = 80$

$\epsilon_c = 4.7$

$F_c = 4.6 \times 10^{-2}$,

we get

$$\underline{\epsilon}_r = \left(0.9638 - 0.9875F_w\right)^{-1}$$

for the lower limit of effective permittivity of the willow/air/water sample as a function of the fractional volume of unbound water it contains at any given time.

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* This follows the development given in Sec. II-D.

The upper limit on ϵ_r, corresponding to dielectric slabs in parallel, is given by:

$$\bar{\epsilon}_r = \sum_{i=1}^{n} \epsilon_i F_i$$

or

$$\bar{\epsilon}_r = 1 + F_w(\epsilon_w - 1) + F_c(\epsilon_c - 1)$$

$$= 1.17 + 79F_w \quad .$$

If the sizes and orientations of the various sample constituents can be determined, it is possible to establish a discrete formula for ϵ_r, rather than simply bounding it. (For instance, a combination of the developments of Wiener[7] and of Kock[8] might be used to describe the sample as a dielectric lens, as suggested by Pounds and La Grone[8].) But we consider such a treatment uncalled for in the analysis of the simple experiment attempted here.

The relationship between ϵ_{rn} as measured with the OWL (Fig. A-3) and the weight of the willows is quite linear during the evaporation of the first 60 or 70 percent of the water. We can define biodensity as the total weight of the willow boughs divided by their volume (as was done for the scale of Fig. A-4). Observe that when there is a reasonable amount of bioplasm* in the boughs there is, again, a linear relationship. It is the biodensity that can be related to biomass and specific gravity as defined by L. T. Burcham,† given data on the heights of the trees covering the areas for which biomass is determined. Burcham defines biomass:

---

* This term is used for the liquid forming the fractional volume assumed to have been lost when the cut willows dried out--assumed to be mostly water with some mineral salts, etc.

† L. T. Burcham, "A Method for Estimating Biomass of Tropical Forests," ARPA Project AGILE Memorandum (29 April and 12 October 1965)--not published.

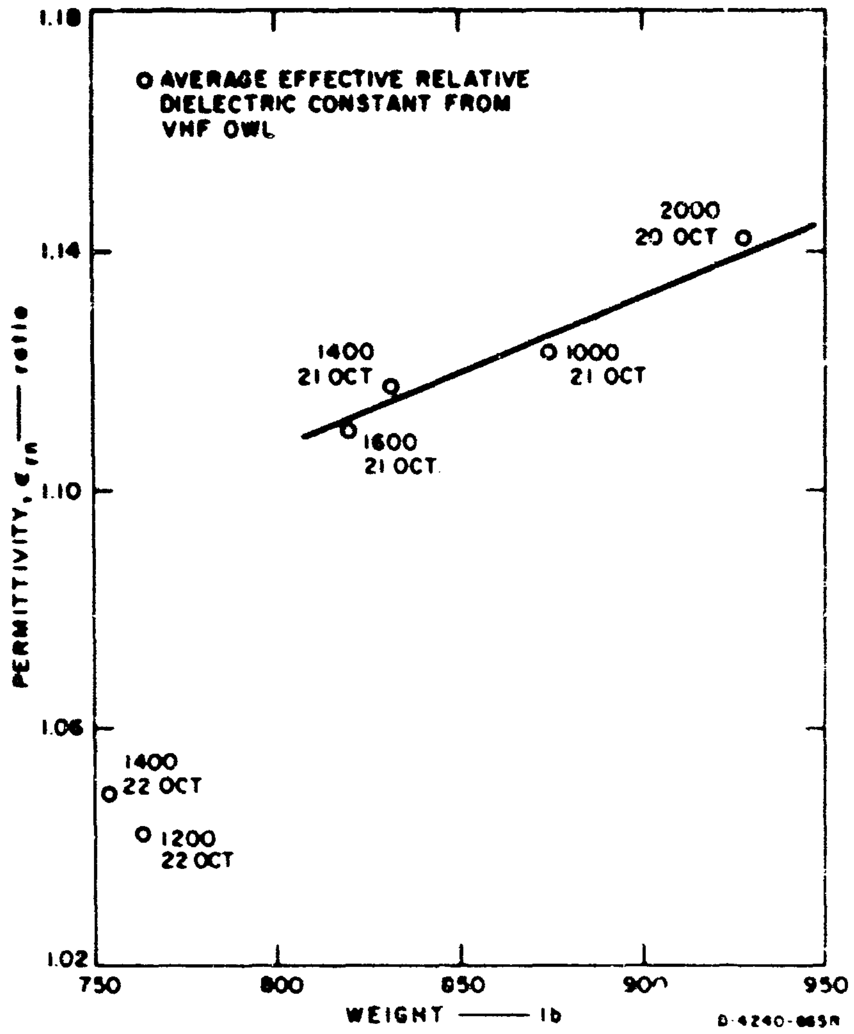

FIG. A-3 CORRELATION OF ϵ_r WITH WATER CONTENT OF WILLOW

> "Biomass refers to the total quantity of plant material in a given plant or plants, or on a specified area. It usually is expressed in terms of weight per plant or weight per unit area, and is directly related to both the cubic content (volume) and specific gravity."

Specific gravity as used by Burcham is presumed to be proportional to bio-density as used in this report, with the constant of proportionality being the density of water (in lb/ft^3).

Values of F_w obtained from weighing the willow sample as it dried, when substituted in the above relations, produced the empirical ϵ curves shown in Fig. A-4, where they are compared with the ϵ_{rn} values obtained from transmission-line measurements taken concurrently. Figure A-4

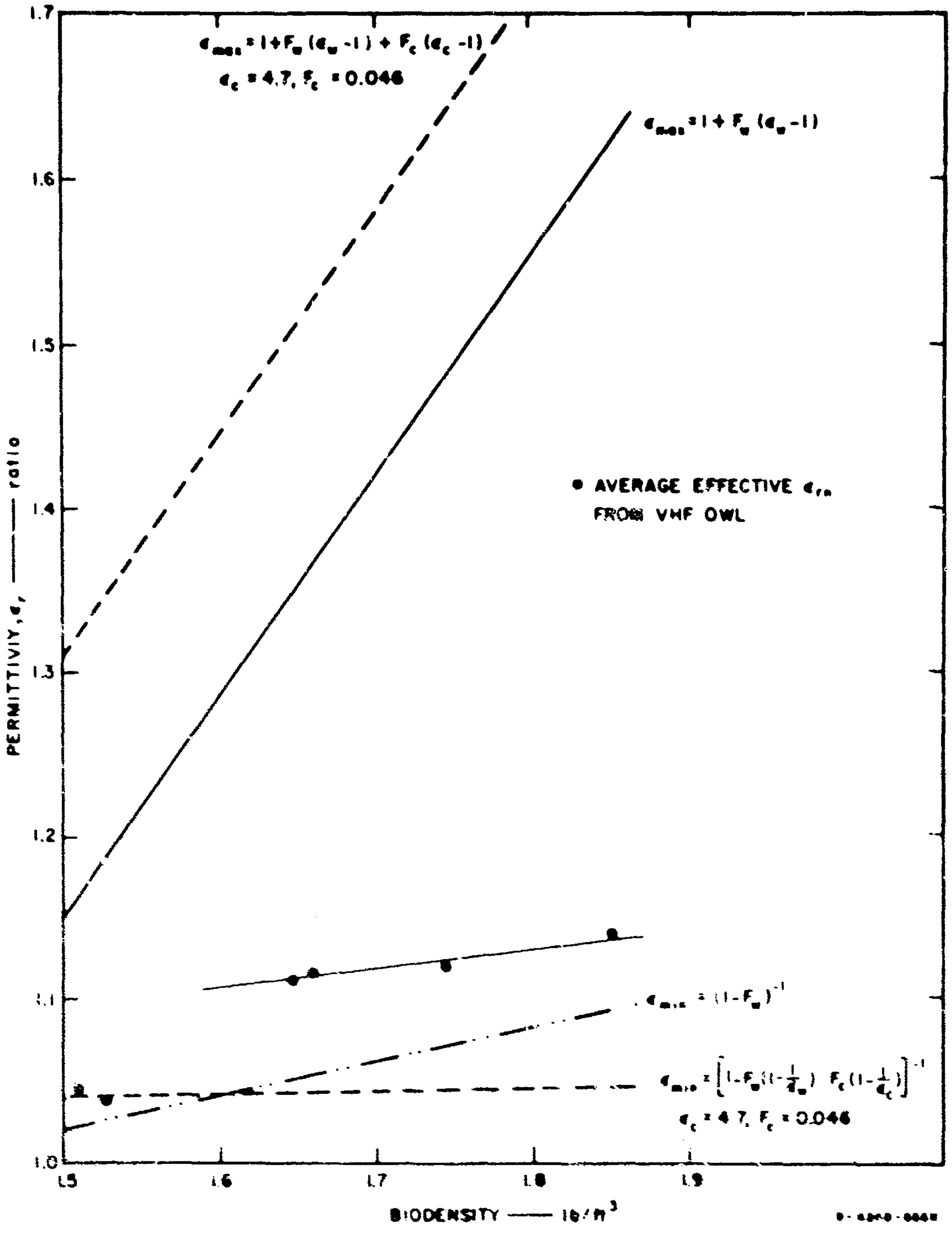

FIG. A-4 CORRELATION OF CALCULATED AND MEASURED PERMITTIVITY WITH BIODENSITY

is a correlation plot, showing the relationships of both methods of gaining effective permittivity to the biodensity of the sample. Either the sample geometry was nearly that of dielectric slabs in series (which seems unlikely), or the presence of the Fiberglas case about the OWL caused a reduction in the ϵ_r values obtained with the OWL. Assuming the latter, we can obtain a rough correction factor to compensate for the presence of the case.

Assuming that the sample geometry was essentially one of parallel slabs, we adopt the upper (dashed) limit as reference and form the functions

$$(\epsilon_{max}-1) \text{ and } (\epsilon_{rn}-1) \quad .$$

Comparing these over the range shown in Fig. A-4, we find that

$$(\epsilon_{max}-1)/(\epsilon_{rn}-1) = 5.0 \pm 0.5$$

where ϵ_{rn} here represents a result of a measurement with the VHF OWL encased in the Fiberglas cylinder. Thus, an approximate correction to account for the presence of the Fiberglas (or absence of some of the sample medium), is to multiply the erroneous value of permittivity, less one, by about 5, and add unity.

The dielectric constant of water is presumed to be relatively insensitive to the type and quantity of mineral salts dissolved in the water. (The dielectric constant of distilled water is about 80 and that for a typical sea water sample about 81.) Thus, for our discussion, ϵ_r is considered independent of the conductivity of the bioplasm. Figure A-5 showing ϵ_{rn} as a function of F_w, indicates that when there was water in the troughs the air/water mixture dominated the complex dielectric constant so far as ϵ_{rn} is concerned.

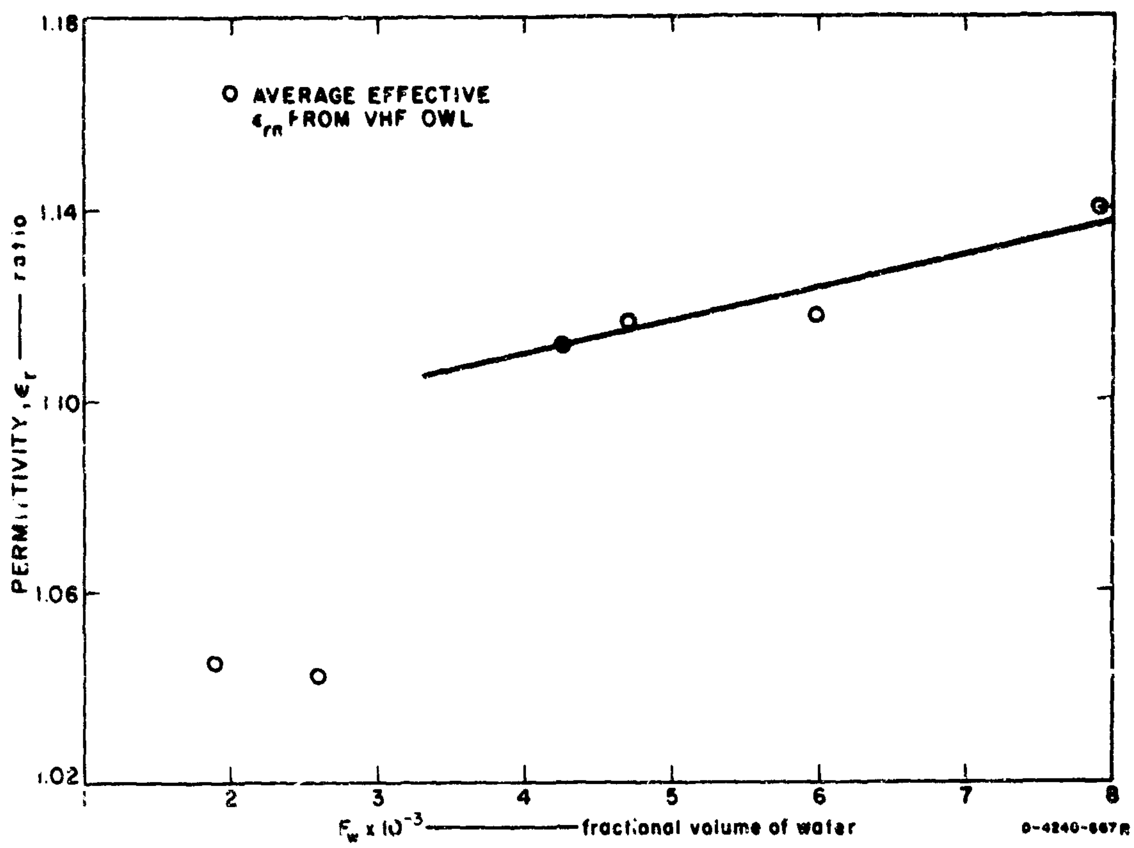

FIG. A-5 CORRELATION OF ϵ_r WITH WATER CONTENT OF WILLOW

Let us now turn to the scaling of conductivity for the willow sample.

4. CONDUCTIVITY

The conductivity of the bioplasm, σ_V, is found from the theory of the complex dielectric constant of mixtures from

$$\sigma_n = \sigma_V F \quad .$$

The fractional volume of water, F_w, has been used to obtain σ_V.

Figure A-6 shows σ_V and the attenuation resulting from its distribution throughout the sample as functions of the sample weight. Note the correspondence between inflection points of the two curves. The conductivity of the wood increases as water evaporates from it, probably because of the resulting increase in the concentration of the salts

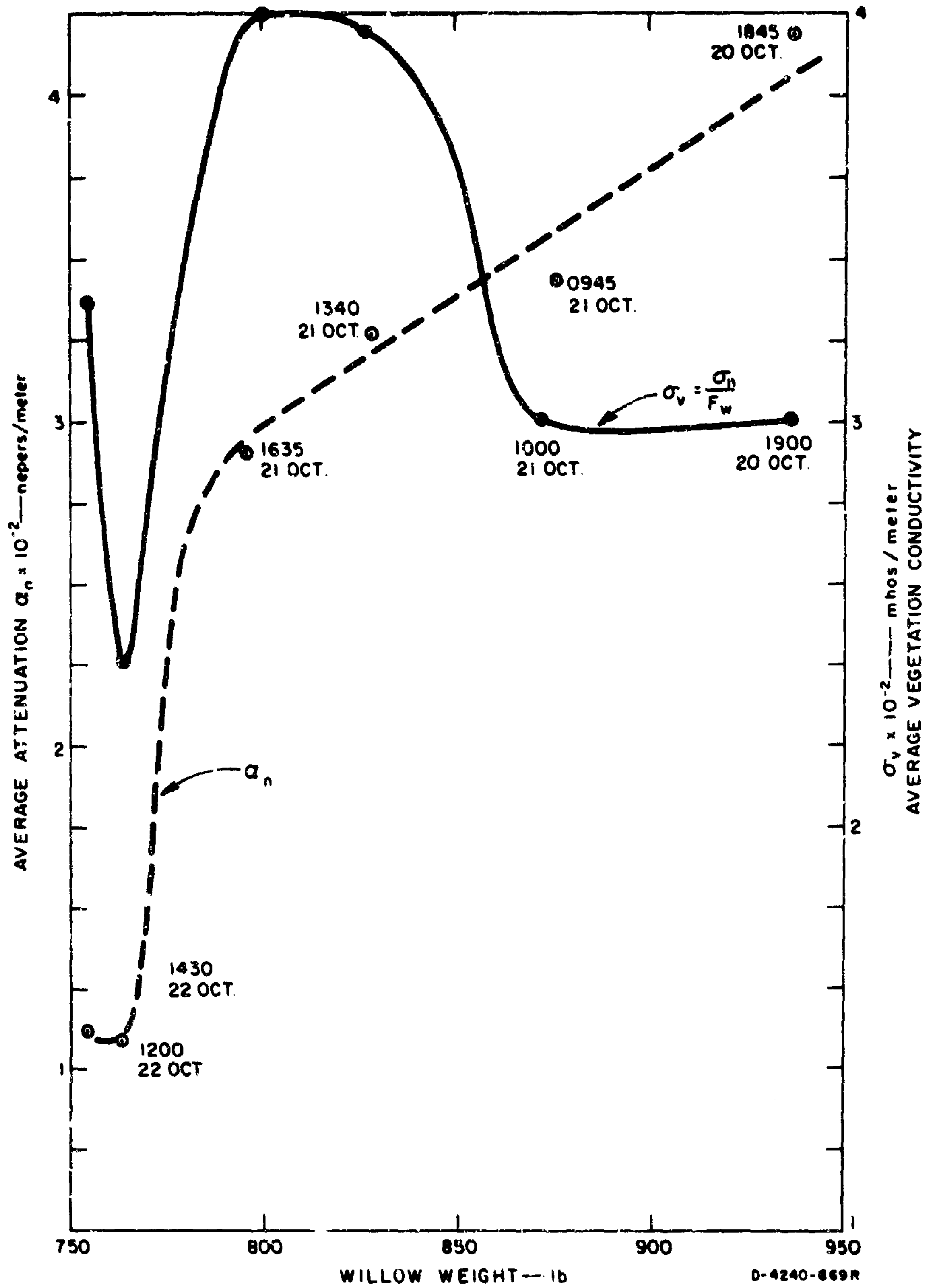

FIG. A-6 VARIATION OF ATTENUATION AND CONDUCTIVITY WITH WILLOW WEIGHT

dissolved in the bioplasm. This effect is apparently not enough to offset the loss of fractional water volume, P_w, which causes attenuation to decrease. The α_n variation was nearly linear, however, during the first day after the willows were cut, indicating a near balance between the two effects until about 1400 on 21 October.

The apparent fluctuations in the σ_v curve occurring before 1600 on 21 October seem to correspond to the rate of water evaporation, as can be seen by the comparison in Fig. A-7. Note that σ_v can apparently be extrapolated backward in time for about one day, indicating that the intrinsic conductivity of the living willow foliage (before noon 20 October) may have been 0.03 mho/meter.

Note also the correspondence between σ_v, α_n and ϵ_{rn} curves for the willow sample, with regard to the fluctuations beginning after 21 October, when about 70 percent of the water had evaporated from the bioplasm. Their variation with time, though ill-defined, seems oscillatory, and may arise from the increasing importance of the diurnal transpiration cycle of the sample (which includes the effect of air humidity), which may involve the exchange of enough water in the last stages of drying to produce the fluctuations observed. Further study of this phenomenon is planned.

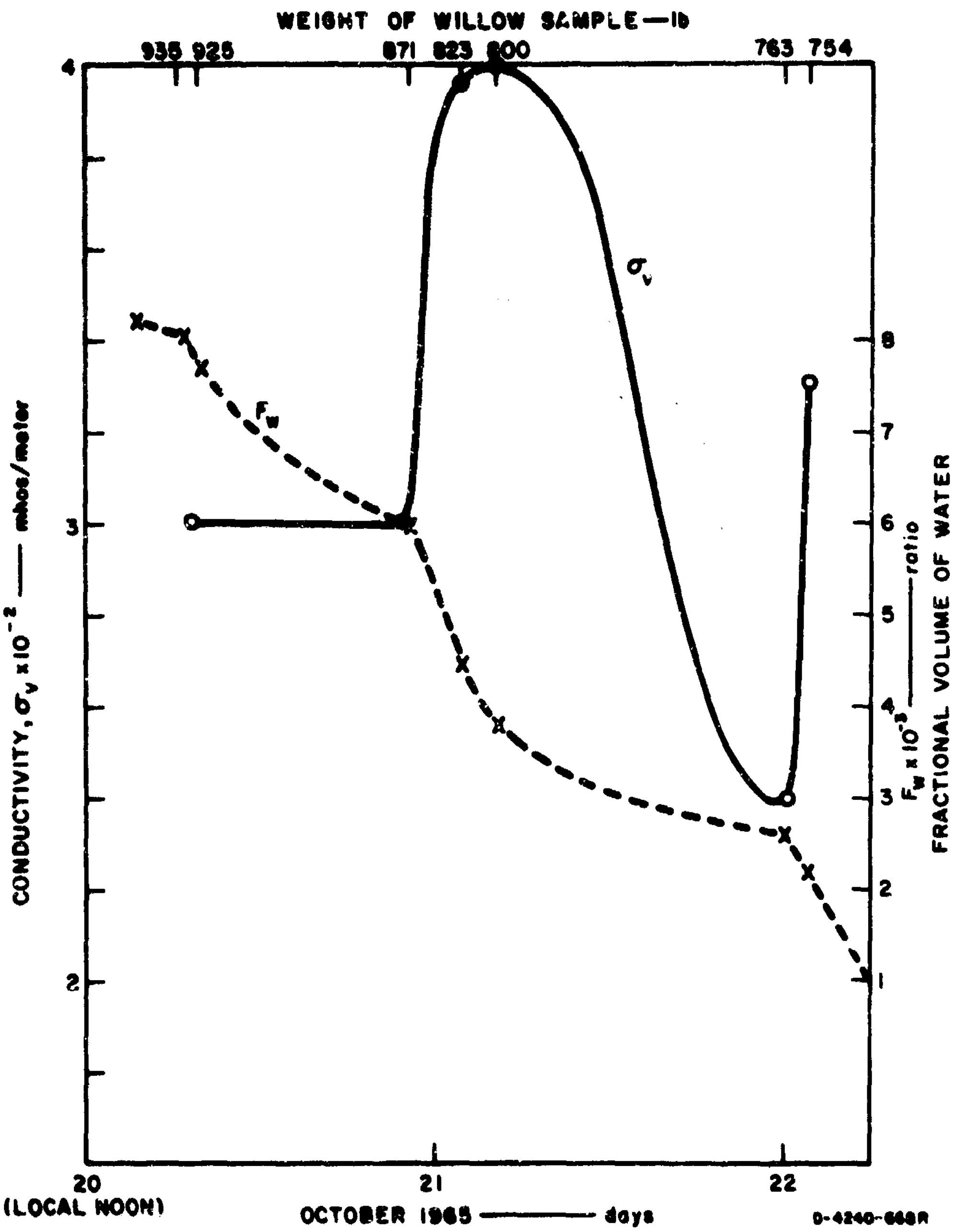

FIG. A-7 VARIATION IN CONDUCTIVITY AND WATER CONTENT IN WILLOW

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13. ABSTRACT

Theory, design, and usefulness of experiments to measure effective complex dielectric constants in foliage and vegetation by means of rigid open-wire transmission lines described. The frequency ranges 30 to 75 MHz (VHF) and 4 to 30 MHz (HF) are covered by using a 5/8-inch-diameter, 3-inch spacing line and a 4-inch-diameter, 40-inch spacing line, respectively. Use of these instruments allows one to place bounds on the macroscopic electrical parameters of foliage.

Results are presented of measurements with these equipments in October 1965 in the Hoh Rain Forest, Olympic National Park, Washington. There, in the most dense growth available, representative values of effective relative permittivity (ϵ_r) and effective conductivity (σ) were estimated to average about 1.2 and 8×10^{-5} mhos/meter, respectively. Similar measurements made in living California foliage in mid-summer 1965 yielded $\epsilon_r \approx 1.06$ and $\sigma \approx 2 \times 10^{-4}$ mhos/meter. Such differences may be seasonal: The need d for a catalog of electrical properties of vegetation is indicated.

An experiment relating the density of freshly cut willow boughs (biodensity) to the properties of the sample measured by the VHF transmission line is described in detail. From this, it is estimated that vegetation intrinsic conductivities are of the order of 0.03 mhos/meter, or greater, in living willows during mid-October. The ϵ_r is linearly related to "biodensity" as indicated by the theory of the complex dielectric constant of mixtures.

Other methods of measurement, such as the use of large capacitors or resonant cavities, are discussed.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Permittivity						
Conductivity						
Attenuation						
Loss tangent						
Lossy dielectric						
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